Operator's Manual

for

LORENTZ FORCE APPARATUS

Sci-Supply model SS20806

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1. INTRODUCTION

The model SS20806 Lorentz Force Apparatus is a complete, self-contained instrument designed to measure the charge-to-mass (*e/m*) ratio of the electron, by means of Lorentz-force deflection of an electron beam. Before operating the apparatus, please read this manual in its entirety in order to gain familiarity with operating procedures and precautions. This will insure good experimental results and long service life.

2. TECHNICAL SPECIFICATIONS

Accelerating voltage: 0 to +250vdc; continuously variable
Magnetizing current: 0 to 2.5A; continuously variable, selectable direction
Deflection voltage: 0 to 250vdc; continuously variable, selectable polarity
Helmholtz coil: 140mm radius; 150 turns
Input power: 120vac 60Hz, 1A
Operating conditions: 0°C to 40°C, RH 20% - 90% (@at 40°C)
Overall dimensions: 350mm x 450mm x 300mm
Weight: ~11kg

3. GENERAL DESCRIPTION

The apparatus consists of a fine-beam electron (Bainbridge) tube mounted between two Helmholtz coils. The tube, coils, and a scale with movable index; are mounted to a steel chassis. The chassis encloses power supplies to provide acceleration voltage to the electron gun, magnetizing current to the Helmholtz coils, and deflection voltage to the deflection plates. The front of the chassis comprises a control panel; from which acceleration voltage, magnetizing current, and deflection voltage may be adjusted and measured. The rear of the chassis is equipped with binding posts for connections to external meters to measure accelerating voltage and magnetizing current. The entire assembly is housed inside an enclosure with blackened interior surfaces to enhance visibility of the electron beam.

4. DETAILED DESCRIPTIONS

An overall layout of the apparatus with feature callouts is shown in Figure 1 on page 5. Annotations giving descriptions of their corresponding callouts follow:

1 – Bainbridge tube: The Bainbridge tube is a fine-beam electron gun housed within a large spherical glass envelope. The electron gun directs an electron beam horizontally to the left. The envelope is filled with low-pressure mercury vapor which emits a blue light along the path of the electron beam. The gun is equipped with upper and lower deflection plates at its muzzle to demonstrate electrostatic deflection of the beam.

2 – Helmholtz coil: The Helmholtz coil is a pair of identical solenoid coils, aligned axially and separated by a distance equal to their radius, in this case 140mm. The coil windings are electrically connected in series-aiding. This particular arrangement produces a very uniform magnetic field within the cylindrical region between the coils when an electrical current is passed through the coils. Each coil has a turn count of 150.

3 – Sliding Index: The sliding index is used to sight the horizontal extremities of the electron beam, in order to measure the diameter of the beam. The top of the index is a V-notch along which the beam is to be sighted.

4 – Scale: The scale is used in conjunction with the sliding index (3) to measure the diameter of the deflected electron beam. It is secured to the apparatus by two clamps. The thumbscrews of the clamps may be loosened and re-tightened in order to align the height of the scale with the horizontal diameter of the beam.

5 – Angular Scale: The angular scale is clamped to the base of the Bainbridge tube (2), and is used to measure the axial rotation of the tube. The angular scale is secured by a tensioning screw, which may be loosened and retightened to adjust the position of the scale on the base.

6 – Fixed Index: The fixed index indicates the axial rotation of the Bainbridge tube (2) against the angular scale (5) on the base of the tube.

7 – Counter-clockwise Magnetizing Current Indicator: The counter-clockwise magnetizing current indicator illuminates to indicate that the direction of the conventional current in the Helmholtz coil is circulating in the counter-clockwise direction. Current direction is selected by the Magnetizing Current direction switch (11).

8 – Clockwise Magnetizing Current Indicator: The clockwise indicator illuminates to indicate that the direction of current in the Helmholtz coil is clockwise. Current direction is selected by the Magnetizing Current rocker switch (11).

9 – Dark Box: The dark box encloses the Bainbridge tube (1) and Helmholtz coils (2). The inside surfaces of the box are painted flat black to enhance visibility of the electron beam in the tube.

10 – Deflection Voltage Dial: The Deflecting Voltage dial is the control with which voltage across the tube's deflecting plates is adjusted. Approximate voltage is indicated by the pointer on the knob, against a scale printed on the front panel. This dial should be at full counter-clockwise during the *e/m* experiment.

11 – Deflection Voltage Polarity Switch: The Deflecting Voltage polarity switch is a three-position rocker switch with which polarity of deflecting voltage is selected: upper plate positive in the upper position; upper plate negative in the lower position; and voltage off in the center position. This switch should be in the center [OFF] position during the *e/m* experiment.

12 – Accelerating Voltage Control Dial: The Accelerating Voltage control dial is the control with which accelerating voltage to the tube's electron gun is adjusted. This voltage is indicated by the associated panel meter.

13 – Magnetizing Current Direction Switch: The Magnetizing Current direction switch is a three-position rocker switch with which direction of (conventional) magnetizing current in the Helmholtz Coil (2) is selected: clockwise in the upper position; counter-clockwise in the lower position; and current off in the center [OFF] position. Direction of current is confirmed by the illuminated indicator lamp (7 or 8). To prevent arcing at the switch contacts, the current control dial (14) should be at full counter-clockwise before operating this switch.

14 – Magnetizing Current Control Dial: The Magnetizing Current control dial is the control with which magnetizing current to the Helmholtz coil (2) is adjusted. Current direction is selected with the direction switch (13), and is indicated by the associated panel meter.

15 – Power Switch: This switch controls the mains power. The switch illuminates when mains power is turned on.

Rear Panel: Binding posts for external meters to measure Accelerating Voltage and Magnetizing Current are located at the rear panel. When using an external current meter, remove the shorting bar from across the Magnetizing Current posts. Also at the rear panel are the power cord receptacle and 1A mains fuse.

Figure 1: General Layout

5. THEORY of OPERATION

The Lorentz force is the magnetic force exerted on a moving electric charge by a magnetic field in which the charge is immersed. This force is expressed in vector notation as

$$\bar{F} = q\,\bar{v} \times \bar{B} \qquad (1a)$$

where
F is the force in newtons,
q is the electric charge in coulombs,
v is the velocity in meters per second, and
B is the magnetic flux density in webers per square meter.

By vector cross-product, this force is perpendicular to both the charge velocity and the magnetic flux. If charge velocity and magnetic flux are themselves perpendicular, all three vectors are mutually perpendicular; the Lorentz force then has magnitude

$$F = q\,v\,B\,. \qquad (1b)$$

A force on an object perpendicular to the velocity of the object results in circular motion of the object; so the Lorentz force in this case is a centripetal force acting in opposition to a centrifugal force of magnitude

$$F = \frac{mv^2}{r} \qquad (2)$$

where
m is the mass of the object in kilograms, and
r is the radius of the circular path in meters.

Equating these forces, and setting $q = e$ (the charge on the electron) and $m = m_0$ (the mass of the electron), yields

$$e\,v\,B = \frac{m_0 v^2}{r}\,. \qquad (3)$$

Dividing both sides of equation 3 by $m_0 vB$ yields

$$\frac{e}{m_0} = \frac{v^2}{vrB} = \frac{v}{rB}\,. \qquad (4)$$

An electric charge e accelerated through a voltage V attains a final kinetic energy equal to its initial potential energy eV, so that

$$\frac{1}{2} m_0 v^2 = e\,V\,. \qquad (5)$$

Solving for velocity yields

$$v = \sqrt{\frac{2\,eV}{m_0}}\,. \qquad (6)$$

Squaring equations 4 and 6, substituting, and canceling terms yields

$$\frac{e}{m_0} = \frac{2V}{r^2 B^2} \ .$$

(7)

By the Biot-Savert Law, the magnetic flux density at the axis of a solenoid coil (of which the Helmholtz coil is an instance) is

$$B = \frac{8\mu_0}{5\sqrt{5}} \frac{IN}{R}$$

(8)

where
μ_0 is the permeability of free space ($4\pi x 10^{-7}$ $c^{-2} \cdot N \cdot s^2$),
I is current through the coil winding in amperes,
N is the number of turn in the coil winding, and
R is the radius of the coil in meters.

Squaring equation 8, substituting into equation 7, and combining terms yields

$$\frac{e}{m_0} = \frac{125}{32\mu_0^2} \frac{V R^2}{r^2 I^2 N^2} \ .$$

(9)

Since voltage, radius of the coils, radius of the electron path, current through the coils, and number of turns in the coils can all be measured; the charge-to-mass ratio of the electron can be determined by this means.

The general procedure in this experiment will be to measure the radius of the electron beam path in the Bainbridge tube for a number of conditions of accelerating voltage and magnetizing current. The measured values of voltage, current, and radius for each condition; along with the number of turns in the coil and the coil radius; are substituted into equation 9. The results for all conditions are averaged to obtain a final value of the charge-to-mass ratio of the electron.

The charge on the electron (as determined in the Millikan oil drop experiment, for example), can be divided by this ratio to determine the mass of a single electron.

6. INITIAL SETUP
Note: Before applying power to the apparatus, familiarize yourself with the operating precautions in Section 9.

External meters may be connected to the rear-panel binding posts to measure accelerating voltage and magnetizing current, if higher precision is desired.

Step 1: Set the apparatus controls as follows: deflection voltage at minimum, deflection voltage polarity to "off", accelerating voltage at minimum, magnetizing current at minimum, magnetizing current direction to "off", power to "off". Connect a power cord to the receptacle on the rear of the apparatus, and plug it into a 120vac outlet.

Step 2: Turn the apparatus on. Verify that the tube filament illuminates. Allow the cathode to heat up for a few minutes.

Step 3: Slowly bring accelerating voltage up to about 100 volts, at which point a continuous horizontal beam of electrons will suddenly emit from the electron gun.

Step 4: Set the magnetizing current direction switch to "clockwise", and adjust current to about 1 ampere. This sets up a magnetic field between the coils, with flux *parallel to the axis of the coils*. Note that the electron beam, now immersed in the magnetic field, describes a circular path inside the tube. Rotate the tube in its socket as necessary to eliminate any axial component of velocity.

7. MEASUREMENT of the *e/m* RATIO of the ELECTRON

Step 1: Set accelerating voltage to 100 volts and magnetizing current to 1.0 amps as measured on the panel meters; record these values on your data sheet.

Step 2: Position your eye directly in front of the left side of the beam's arc. Slide the index along the scale until its position is directly in line with the left side of the arc. It may be necessary to adjust the height of the scale. Record the index position on your data sheet. Repeat this step for the right side of the beam.

Step 3: Repeat Steps 1 and 2 with magnetizing currents of 1.25, 1.5, 1.75, and 2.0 amps.

Step 4: Repeat Steps 1 through 3 with acceleration voltages of 125, 150, 175, and 200 volts.

Step 5: Calculate the ratio *e/m* for each combination of accelerating voltage and magnetizing current in the data set. The radius of the beam is ½ the difference between the left and right index positions. Use a coil radius of 140mm, and a coil turn count of 150.

Step 6: Average all calculated values to arrive at a final value of *e/m*. An example data set is shown in Table 1 on page 10 of this document.

Step 7: From the value of the charge on the electron, calculate the mass of the electron.

8. INCIDENTAL DEMONSTRATIONS

Component of Charge Velocity Parallel to B: The socket for the Bainbridge tube is mounted to the chassis of the apparatus so that it can be rotated axially. The effect of rotating the tube is to "aim" the electron gun from side to side, thus imparting to the beam a component of velocity parallel to the magnetic flux.

By vector cross-product, the Lorentz force on this parallel component of velocity is zero, so this component of the beam is not deflected. Meanwhile, the Lorentz force acts on the perpendicular component as it does in the e/m measurement, causing the beam to deflect in a circular path perpendicular to the flux.

The superposition of these two motions is a helical path, with its axis parallel to the flux. Rotating the tube to various degrees changes the magnitude of the parallel component of velocity, thus changing the pitch of the helix.

The base of the tube is fitted with an angular scale, and the chassis with a fixed index, to indicate the angle to which the tube is rotated.

Electrostatic Deflection of the Electron Beam: An electron beam will also be deflected by an electric field, but in a different way as by a magnetic field. The electron gun in the Bainbridge tube is equipped with static deflection plates at its muzzle. When a voltage is impressed across these plates, an electric field is set up between them.

As the electron beam passes between the plates and through this electric field, the beam is deflected by an angle. This angle increases with field intensity (controlled by the deflecting voltage); and decreases with beam velocity (controlled by the accelerating voltage). Reversing the polarity of the voltage reverses the direction of deflection. Note: Magnetizing current should be turned off for this effect to best be seen. Do not permit the beam to strike any single point of the tube's glass envelope for an extended time.

9. OPERATION, HANDLING, and STORAGE

Although the Bainbridge tube will deliver reliable service over many hours of operation, it should still be considered a life-limited device. Following these guidelines will maximize tube life:
- Allow the tube to warm up for a few minutes before applying accelerating voltage. Bring accelerating voltage up slowly.
- During operation of the tube, do not allow the electron beam to strike any one point on the tube envelope for an extended time; this would result in erosion and eventual puncture of the glass envelope.
- Limit the duration of operating sessions to one hour.
- When rotating the tube in the socket (or when removing the tube from the socket), grasp the tube by its bakelite base, not by the glass neck.
- Protect the tube from scratches and sharp impacts. If the apparatus is to be stored for an extended time, remove the tube from the apparatus and store it separately in its original packing box.

Additional operating guidelines:
- Adjust the magnetizing current to minimum before operating the magnetizing current direction switch.
- Turn all controls to minimum and all switches to center-off before turning power on or off.

Protect the apparatus from vibration, shock, and moisture.

Install the protective cover over the front of the enclosure between uses.

Store the apparatus in a cool, dry location.

THE CHARGE-TO-MASS RATIO OF THE ELECTRON

Radius of Helmholtz Coils
R =   140 mm =   0.140 m

Number of Turns on Helmholtz Coils
N =   150

Accel voltage V (V)	Magnetizing current I (A)	Electron beam			e/m ratio (c/kg)
		s_1 (cm)	s_2 (cm)	r (m)	
100	1.00	7.1	14.1	0.0350	1.759E+11
100	1.25	7.7	13.2	0.0275	1.824E+11
100	1.50	8.1	12.8	0.0235	1.734E+11
100	1.75	8.4	12.4	0.0200	1.759E+11
100	2.00	8.7	12.2	0.0175	1.759E+11
				Avg:	1.767E+11
125	1.00	7.0	14.8	0.0390	1.771E+11
125	1.25	7.8	14.0	0.0310	1.794E+11
125	1.50	8.3	13.5	0.0260	1.771E+11
125	1.75	8.6	13.1	0.0225	1.737E+11
125	2.00	8.9	12.8	0.0195	1.771E+11
				Avg:	1.769E+11
150	1.00	6.9	15.5	0.0430	1.748E+11
150	1.25	7.7	14.6	0.0345	1.738E+11
150	1.50	8.3	13.9	0.0280	1.832E+11
150	1.75	8.6	13.5	0.0245	1.758E+11
150	2.00	8.9	13.2	0.0215	1.748E+11
				Avg:	1.765E+11
175	1.00	6.5	15.9	0.0470	1.707E+11
175	1.25	7.5	14.9	0.0370	1.763E+11
175	1.50	8.0	14.2	0.0310	1.744E+11
175	1.75	8.5	13.8	0.0265	1.753E+11
175	2.00	8.8	13.5	0.0235	1.707E+11
				Avg:	1.735E+11
200	1.00	6.4	16.3	0.0495	1.759E+11
200	1.25	7.2	15.1	0.0395	1.768E+11
200	1.50	7.9	14.4	0.0325	1.813E+11
200	1.75	8.3	13.9	0.0280	1.795E+11
200	2.00	8.6	13.5	0.0245	1.795E+11
				Avg:	1.786E+11

	Actual	Calculated	Error
e/m (c/kg)	1.7588E+11	1.7643E+11	0.313%
e (c)	1.6022E-19	—	—
m_o (kg)	9.1094E-31	9.0810E-31	0.312%

Table 1 – Sample Data Set

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