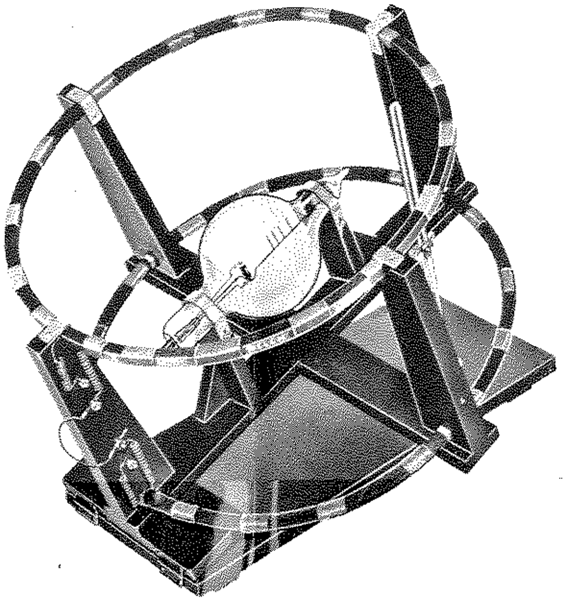
Instructions for Operating
Cat. No. 623 e/m Vacuum Tube
and
Cat. No. 623A Helmholtz Coils



Description

No. 623 *e/m* Vacuum Tube has been designed for determining the ratio of charge to mass of an electron. It may also be used to demonstrate the curving of a beam of charged particles as they pass through a magnetic field, and as an aid in explaining the principle of the mass spectrometer. No. 623A Helmholtz Coils have been designed large and rigid to provide the uniform magnetic field required in the operation of the tube. The axis of the coils may be inclined to the dip angle for quantitative measurements and to a horizontal position for classroom demonstrations.

The tube is essentially the same as one described by K. T. Bainbridge (American Physics Teacher **6**, 35, 1938) who states that "Historically the method is of great interest as, in principle, it is the same as that described by A. Schuster in 1890 (Proc. Roy. Soc. **47**, 526, 1890) and used by W. Kaufman in 1897 (Wied. Ann. **61**, 544, 1897)." The present apparatus is based upon an improved version built and extensively tested by Professor Ralph P. Winch, Williams College, and incorporates various additional improvements developed in our own laboratory.

The beam of electrons in the tube is produced by an electron gun composed of a straight filament surrounded by a coaxial anode containing a single axial slit. See Fig. 1a and 1b for schematic diagrams of the tube. Electrons emitted from the heated filament F are accelerated by the potential difference applied between F and the anode C. Some of the electrons come out as a narrow beam through the slit S in the side of C. When electrons of sufficiently high kinetic energy (10.4 electron volts or more) collide with mercury atoms, mercury vapor being present in the tube, a fraction of the atoms will be ionized. On recombination of these ions with stray electrons the mercury-arc spectrum is emitted with its characteristic blue color. Since recombination with emission of light occurs very near the point where ionization took place, the path of the beam of electrons is visible as the electrons travel through the mercury vapor.

The magnetic field of the Helmholtz Coils causes the stream of electrons to move in a circular path the radius of which decreases as the magnetic field increases. By proper control of the magnetic field the sharp outer edge of the beam can be made to coincide with any one of five bars spaced at known distances from the filament.

Each coil of the pair of Helmholtz Coils has 72 turns of copper wire with a resistance of approximately one ohm. The approximate mean radius of the coil is 33 centimeters. The coils are supported in a frame which can be adjusted with reference to the dip angle so that their magnetic field will be parallel to the earth's magnetic field but oppositely directed. A graduated scale indicates the angle of tilt. A safety device prevents the coils from accidentally dropping back to the horizontal. Wooden seats with retaining straps cradle the tube in a central plane midway between the two coils.

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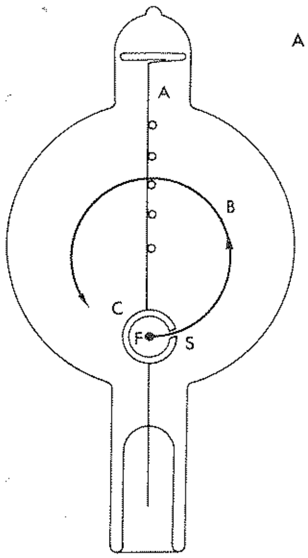

Fig. 1a.

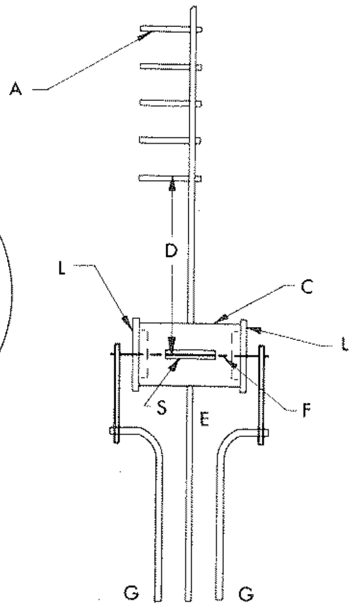

Fig. 1b.

Fig. 1a is a sectional view of the tube and filament assembly. Fig. 1b is a detailed section of the filament assembly at right angles to Fig. 1a.

A. Five cross bars attached to staff wire.
B. Typical path of beam of electrons.
C. Cylindrical anode.
D. Distance from filament to far side of each of the cross bars.
E. Lead wire and support for anode.
F. Filament.
GG. Lead wires and supports for filament.
LL. Insulating plugs.

Theory

When a charged particle such as an electron moves in a magnetic field in a direction at right angles to the field, it is acted on by a force the value of which is given by

$$f = Bev \tag{1}$$

where B is the magnetic flux density in webers/meter^2, e is the charge on the electron in coulombs, and v is the velocity of the electron in meters/sec.

This force causes the particle to move in a circle in a plane perpendicular to the magnetic field. The radius of this circle is such that the required centripetal force is furnished by the force exerted on the particle by the magnetic field. Therefore

$$\frac{mv^2}{r} = Bev \tag{2}$$

where m is the mass of electron in kilograms, and r is the radius of circle in meters, i.e., ½D.

If the velocity of the electron is due to its being accelerated through a potential difference V, it has due to its velocity a kinetic energy of

$$\tfrac{1}{2}mv^2 = eV \tag{3}$$

where V is the accelerating potential in volts.

Substituting the value of v from Eq. (3) into Eq. (2)

$$\frac{e}{m} = \frac{2V}{B^2r^2} \tag{4}$$

Thus when the accelerating potential, the flux density of the magnetic field, and the radius of the circular path described by the electron beam are known, the value of e/m can be computed, and is given in coulombs/kg by Eq. (4) if V is in volts, B is in webers/m^2 and r is in meters. Note. Eq. (4) will give e/m in the electromagnetic units of abcoulombs/gm if V is in abvolts, B is in gauss, and r is in cm.

The magnetic field which causes the electron beam to move in a circular path has the magnetic flux density B (in webers/m^2) which, in terms of current through the Helmholtz coils and certain constants of the coil, is

$$B = \frac{8\mu_0 NI}{\sqrt{125}\,a}\,^{*} \tag{5}$$

where N is the number of turns of wire on each coil,
I is the current through coils in amperes,
a is the mean radius of coil in meters,
μ_0 is the permeability of empty space, which is $4\pi \times 10^{-7}$ weber/ampere meter.

Substituting Eq. (5) in Eq. (4) gives

$$\frac{e}{m} = \left(\frac{3.91}{\mu_0^2} \cdot \frac{a^2}{N^2}\right)\frac{V}{I^2r^2}$$

$$= \left(2.47 \times 10^{12}\ \frac{a^2}{N^2}\right)\frac{V}{I^2r^2} \tag{6}$$

Note. See Supplementary Comments at end of these instructions for Eq. (5) and (6) expressed in the electromagnetic system of units.

Eq. (6) is the working equation for this apparatus. The quantity within parentheses is a constant for any given pair of Helmholtz Coils. The value of r, the radius of the electron beam, can be varied by changing either the accelerating potential or the Helmholtz field current. For any given set of values, the value of e/m can be computed.

Accessory Apparatus

The following apparatus will be needed to perform this experiment. Most of it, or the equivalent, will normally be already on hand. See circuit diagrams, Fig. 2 and 3.

Filament Circuit

D.C. ammeter, 10 ampere range. Welch No. 3031J.
Slide Wire Rheostat, 2.5 ohms. Welch No. 2751.
Storage Battery, 6 volts. Welch No. 2307C.

Accelerating Circuit

D.C. Milliammeter, 25 ma range. Welch No. 3034P.
High-resistance D.C. Voltmeter, 50 volt range. Welch No. 3018K.
"B" battery (22½ and 45 volts) for accelerating voltage. Welch No. 2265A.

Field Circuit

D.C. Ammeter, 5 ampere range. Welch No. 3000B.
Slide Wire Rheostats, 5.0 ohms and 170 ohms. Welch No. 2751.
Two Storage Batteries, 6 volts each. Welch No. 2307C.

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*Ralph P. Winch, *Electricity and Magnetism*. Prentice-Hall, Inc., 1955, pp 504—506.

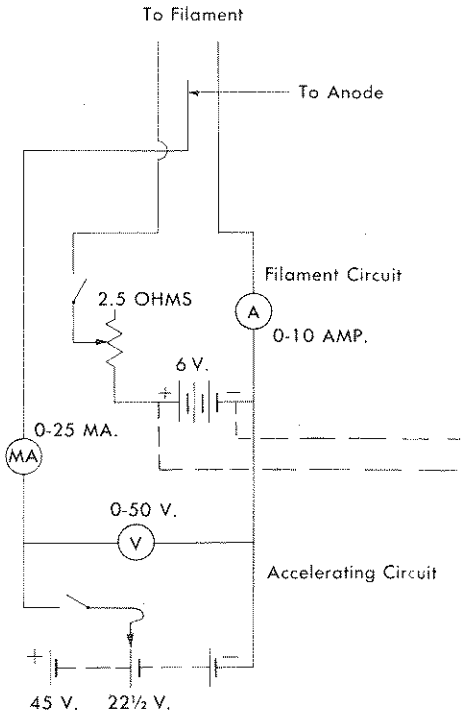
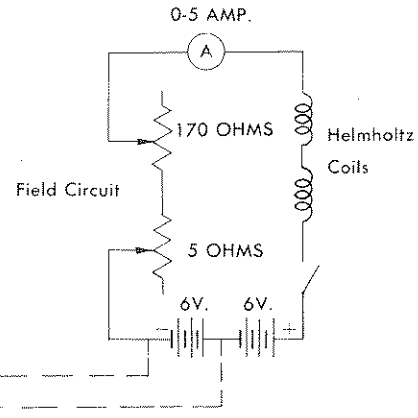


Fig. 2



Tap off for filament power
if separate filament battery
not available.

Fig. 3

In addition, three knife-type switches such as Welch No. 2990 will be desirable. A magnetic dip needle, such as Welch No. 1875 or 1879, will also be needed. In the event that the experiment is to be performed by only a few students, six-volt dry batteries, such as Welch No. 2239, may be substituted for the storage batteries listed above. Variable carbon rheostats, such as Welch No. 2748H, may be substituted for the 2.5-ohm and the 5-ohm slide wire rheostats.

Setting Up the Apparatus

The Helmholtz-Coils assembly may be partially "knocked down" for shipment. The parts removed are a long slotted and graduated strip attached to a flush plate, a right angle casting with clamp, and a rubber bumper. The rubber bumper is to be located on the base board so it will be beneath the bumper on the hinged board. The flush plate is attached to the base board in its place located by the three screws. The right-angle casting with clamp is attached to the under side of the hinged board. This is to be used as a friction brake and should be so regulated that if the clamp screw is loosened while the *e/m* tube is mounted, the hinged board will settle slowly without shock.

The room should be fairly well darkened for demonstrating and making measurements with the *e/m* tube. If a table about 16 inches high is available, its use will permit the observer to lean over the Helmholtz Coils and view the beam perpendicular to its plane. If the coils are placed on a table of normal height the observer will have to stand on a chair to see the beam from the proper direction. The wooden box used for shipping the coils is of the right height to make a good support on which to place the apparatus. Its use is suggested if a table or other support is not available.

Place the tube in its support in the center of the frame. The end of the tube from which the leads extend should be adjacent to that part of the frame on which connectors are mounted. Secure the tube in place with the straps.

Orient the Helmholtz Coils so that the *e/m* tube will have its long axis in a magnetic north-south direction, as determined by a compass. Measure the magnetic inclination at this location with a good dip needle. Tip the coils up until the plane of the coils makes an angle with the horizontal equal to the complement of the dip angle. The axis of the coils should now be parallel to the earth's magnetic field.

Make electrical connections to the tube as shown in Fig. 2. Use a 6-volt storage battery to supply the filament current. (It may be one of the two used in the field coil circuit.) Use a slide-wire rheostat of 2.5-ohm resistance to control the filament current. An ammeter of 5- or 10-ampere range and 2% accuracy is satisfactory for measuring this current. Use a high resistance voltmeter of 1000 ohms per volt, or higher, to measure the accelerating voltage accurately. A voltmeter of 0.5% accuracy, or better, is essential here.

Make electrical connections to the Helmholtz Coils as shown in Fig. 3. The ammeter used in this circuit for measuring the field current should have 0.5% accuracy or better. The two coils are connected in series and the current sent through them in such a direction that their magnetic field is oppositely directed to the earth's field. Knife-type switches in each of the three circuits, as shown, will be helpful. Tape any bare connections at the tube to avoid short circuits.

Operation

The filament of the e/m tube has the proper electron emission when carrying 2.5 to 4.5 amperes. Exceeding 4.5 amperes will materially shorten the tube's life. Good results can be obtained using an accelerating voltage of 22½ to 45 volts. An electron emission current of 5 to 10 ma gives a visible beam. For maximum filament life operate the tube with the minimum filament current necessary for proper electron emission. It is helpful and good practice to apply about 22½ volts accelerating potential to the anode before heating the filament. Always start with a low filament current and carefully increase it until the proper electron emission is obtained. Since the electron beam appears suddenly it is advisable to increase the filament current slowly to avoid overheating and possibly burning out the filament.

Apply 22½ volts accelerating potential to the tube. With maximum resistance in the filament circuit, close the switch in this circuit. Gradually decrease this resistance until the milliammeter indicates 5 to 10 ma and the electron beam strikes the tube wall. Rotate the tube in its cradle until the electron beam is horizontal and the bars extend upward from the staff wire. Note that the electron beam is deflected slightly toward the base of the tube by the earth's magnetic field.

Now send a small current through the Helmholtz Coils. If the magnetic field of the coils straightens the beam or curves it in the opposite direction, the coils are correctly connected. If this field increases the deflection toward the base, the current is flowing through the coils in the wrong direction and the connections must be reversed. If no effect is observed on the beam, the field due to one coil is opposing that of the other and connections to one coil must be reversed. Make any necessary changes and increase the field current sufficiently to cause the beam to describe a circular path without striking the wall of the tube. The apparatus should now be ready for obtaining the necessary data to compute the value of e/m.

Data and Results

In the manufacture of the e/m tubes the crossbars have been attached to the staff wire and this assembly attached to the filament assembly in precise fixtures which accurately control the distances between the several crossbars and the filament. Distances given are to the far side of the crossbar.

Crossbar Number	Distance to Filament (D)
1	0.065 meter
2	.078 "
3	.090 "
4	.103 "
5	.115 "

These distances are the diameters of the several circles which the electron beam will be caused to describe.

Following the prescribed procedure, heat the filament until the electron beam is visible. Allow a few minutes for warm up and temperature equilibrium.

Close the circuit comprising the Helmholtz Coils and adjust the value of the current until the electron beam is straight. One method is to adjust the beam until it is aligned with a straightedge held as close to the tube as possible. Another method is as follows. Increase the current through the coils until the beam shows a slight curvature as compared with the straightedge and record the value of the current. Then decrease the current until the beam shows an equal curvature in the opposite direction and record the current. The average of these values will be the value of the current required to straighten the beam. This adjustment should be made carefully and accurately. When the beam is straight the magnetic field of the coils just equals the earth's magnetic field. Record the value of this current as I_1 in a table similar to Table I. The value of I_1 is constant as long as the accelerating voltage, V, remains the same. When V is changed the value of I_1 must be redetermined.

Table I.

Crossbar No.	r	V	I_1	I_2	I	e/m

Increase the field current until the electron beam describes a circle. Adjust its value until the sharp outside edge of the beam strikes the outside edge of a crossbar. Record this value as I_2 in the table. The outside edge of the beam is used because it is determined by the electrons with the greatest velocity. The electrons leaving the negative end of the filament fall through the greatest potential difference between filament and anode, and have the greatest velocity. It is this potential difference which the voltmeter measures.

Determine and record the field current required to cause the electron beam to strike each of the other bars. Subtract I_1 from each value of I_2 and record as I.

This is the value of the current to be used in Eq. (6) for computing e/m. Compute e/m for each value of I.

Repeat the above and determine e/m using a different value of accelerating voltage such as 45 volts. Compare the results with the accepted value of e/m, which is 1.76 x 10^{11} coulomb/kg.

Supplementary Comments

By subtracting the field current just necessary to overcome the earth's field from the total field current required to curve the beam into a given circular path, the effect of the earth's field on the determination of e/m is eliminated and there is no need to know or otherwise determine the earth's magnetic field. However, if desired, the value of the earth's magnetic field may be computed using the value of I_1 in Eq. (5).

The tube can be used quite effectively as a demonstration in a well-darkened lecture room. For the most effective demonstration the whole unit should be tipped until the axis of the coils is nearly horizontal. In this position the tube and the beam of electrons are most easily seen by the class.

The action of this e/m tube and Helmholtz Coils can be used in explaining the principle of a mass spectrometer. A consideration of Eq. (6) shows that for charged particles carrying the same charge but differing in mass the radius of the circular path into which they are caused to move by the magnetic field differs for particles of different masses. Knowing the value of the charge and measuring the radius of the circular path, the mass of particles can be determined. This is essentially what is done in a mass spectrometer.

If the magnetic field of the Helmholtz Coils is increased sufficiently to cause the electron beam to describe a circle of small radius, then by rotating the tube slightly the beam will spiral either upward or downward. Reversing the filament current will reverse the direction of the spiral, the spiraling of the beam being caused by the magnetic effect of the filament current. A reversing switch in the filament circuit is helpful during this demonstration.

In the electromagnetic system of units, Eq. (5) is

$$B = \frac{32 \pi NI}{\sqrt{125}\, a}$$

and Eq. (6) becomes

$$\frac{e}{m} = \left(2.47 \times 10^{-2} \; \frac{a^2}{N^2} \right) \frac{V}{I^2 r^2}$$

where a and r are in cm, V is in abvolts, B is in gauss, and I is in abamperes. In this system the accepted value of e/m is 1.76 x 10^7 abcoulombs/gram.