Electron trajectory in an e/m experiment

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A common undergraduate experiment to measure the e/m ratio uses a magnetic field produced by Helmholtz coils to deflect an electron beam. It is usually assumed that the beam is in the symmetrical plane of the coils and that it is in a uniform field identical to the field at the center of the coils. The magnetic induction field at the central position can be calculated from the geometry of the coils. In this paper the magnetic field in the region of the electron beam is calculated and compared to the field at the center of the coils. The height of the beam increases as it traverses the semicircular path and this increase is calculated.

I. INTRODUCTION

One way to do the e/m experiment is to observe the path of a beam of electrons when they traverse a uniform magnetic field. A common source of this magnetic field is a pair of Helmholtz coils connected in series and carrying a current. It is usually assumed that the magnetic field which exists at the electron's path is the same as the magnitude of the field on the axis of the coils and midway between the coils. The field at the center of an ideal pair of Helmholtz coils is given in Eq. (11). This equation is derived in a number of texts, such as Refs. 16 and 17.

Several articles have appeared which describe power supplies that make this experiment easier for students to perform.[1–4] The spreading of the beam into a fan shape is also mentioned in some of these articles.[2–4] The articles also describe ways that can be used to reduce the spreading so that the beam approximates an ideal beam in the symmetrical plane.

A number of authors have considered the homogeneity of the magnetic field in the central region of a set of Helmholtz coils. For example, see the works cited in Refs. 5–11. They expressed the magnetic field in the region of interest by making a series expansion about the point at the middle of the coil pair. Higbie[12] used a numerical integration technique to calculate the field in the symmetrical plane but for a point off the axis of the Helmholtz coils. The magnetic field at the center of the coils is usually calculated by assuming that the current is conducted by a wire that has a vanishingly small cross section. The effect of the finite cross section of the coil windings has also been calculated.[7,11,13] Normally the distance between the planes of the two Helmholtz coils is equal to the radius of the coils. However, some work indicates that the field uniformity can be improved by using a slightly different spacing.[14,15]

While carrying out an experiment to measure the e/m ratio some undergraduate students wanted to know how the magnetic field at the center of the coils compared to the actual field in the region of the beams path. They also wondered why the beam of electrons spread out forming a fan-shaped pattern on a cylindrical surface. One way that each of these questions can be answered is given in the following sections. The method for calculating the magnetic field at an arbitrary point in the central region of the Helmholtz coils used in this paper is based upon a procedure outlined in the texts by Reitz, Milford, and Christy,[16] and Page and Adams.[17] This procedure was used to show the students that material discussed in class could be used in analyzing an experiment that they had performed. The approach used is at a level appropiate for undergraduate students.

II. APPARATUS

This discussion is based upon apparatus that was obtained from a commercial vendor.[18] The two main components are a set of Helmholtz coils and a Pyrex tube shaped like an early x-ray tube. The tube is shaped roughly like a sphere with two cylinders attached on opposite sides. The cylindrical parts allow the tube to be mounted easily. They also provide support for the components inside the tube and allow vacuum tight electrical feed throughs to the interior components.

Inside of the tube is a source of electrons which will be described in more detail in Sec. IV. The electron beam has a rectangular cross section as it leaves the source which is about 10^{-2} m high and 8×10^{-4} m wide. The tube is mounted so that the source is halfway between the coils. Fig. 1 shows a simplified overview of the experimental arrangement.

The field set up by the Helmholtz coils is quite uniform in the region where the electron beam is observed, so the beam traverses a circular path of radius R_1. That the path is circular is demostrated in many physics texts, and it will not be repeated here. The result is that $e/m = v/BR_1$, where the speed v can be determined from the accelerating voltage V in the source, and R_1 can be found by adjusting the magnetic field B of the Helmholtz coils until the beam hits an indicator inside of the tube. Since the beam travels in a semicircle before hitting the indicator, R_1 can be found by taking one-half of the distance from the electron source to the indicator. The center of this circle coincides with the axis of the coils, and the plane of this circle is parallel to the coils. However, as the bam traverses the semicircle, the height of the rectangular cross section increases slowly so the beam appears to have the shape of a curved fan. The spreading is symmetrical in the direction perpendicular to the circular arc.

A high vacuum was established in the tube, but before it was sealed off, a small amount of mercury was placed in it. Some of the electrons will collide with a few of the mercury atoms and leave the mercury atoms in an excited state. The mercury atoms will go back to their ground states by emitting radiation which is visible to the human eye. The trajectory of the electron beam is then visible to the experimenter. The beam trajectory is indicated in Fig. 2.

III. OFF-AXIS MAGNETIC FIELD

The general procedure that was adopted for this calculation follows the method outlined in some texts,[16,17] but was carried to a higher order than is given in them. The proce-

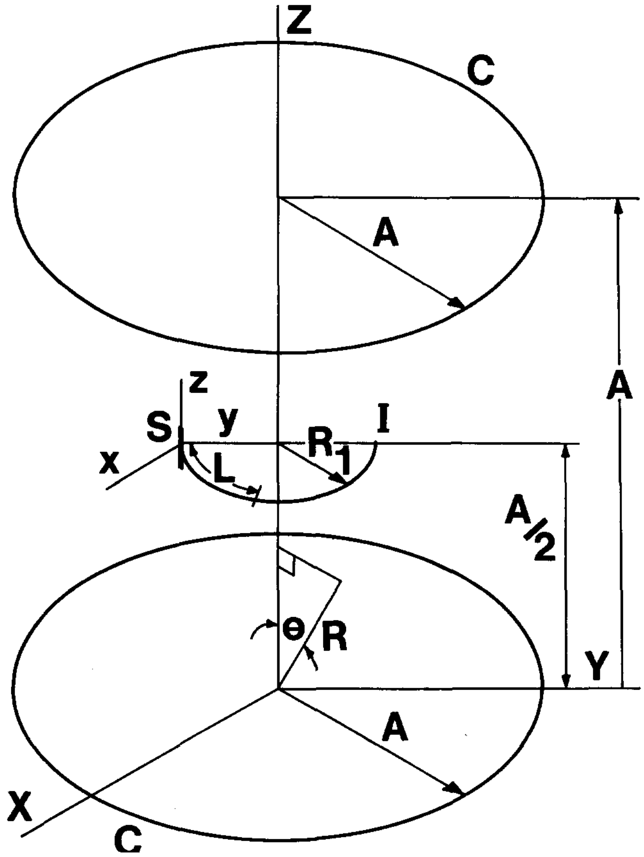

Fig. 1. General layout of *e/m* apparatus. *C*—Helmholtz coils of radius *A*, *S*—electron beam source, and *I*—diameter indicator. The arc length of the electron path is *L*. The origin of the *XYZ* coordinate system is at the center of the lower coil, and the origin of the *xyz* coordinates is at the center of the electron source.

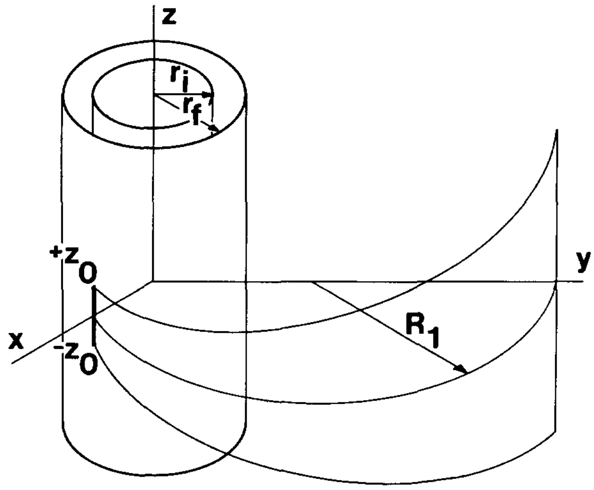

Fig. 2. Electron source detail which shows cylindrical fan shape of beam. R_1 is the radius of fan cylinder.

dure begins by calculating the magnetic field due to circular loop of wire of radius A and carrying a current I. For a coil of N closely spaced turns, the result for a single turn can be multiplied by N to give to field due to the coil.

The magnetic field B outside of a current distribution can be obtained from a scalar potential according to the following expression:

$$\mathbf{B} = -\mu_0 \nabla U, \tag{1}$$

where μ_0 is the permeability of free space and U is the desired potential. For a loop carrying a current I it can be shown that U can be expressed as

$$U = -I\Omega/4\pi, \tag{2}$$

where Ω is the solid angle subtended by the loop at the observation point. For a circular loop of radius A centered at the origin and positioned in the $X-Y$ plane, U can be expressed as

$$U(Z) = [1 - Z(A^2 + Z^2)^{-1/2}]I/2 \tag{3}$$

for an observation point on the Z axis. The coordinates used in this discussion are shown in the lower portion of Fig. 1. Using a binomial expansion for $Z<A$, the radical can be expressed in terms of Z/A giving

$$U(Z) = (1 - Z/A + Z^3/2A^3 - 3Z^5 + 5Z^7/16A^7 - 35Z^9/128A^9 + 63Z^{11}/256A^{11} - \cdots)I/2. \tag{4}$$

Let θ be the angle between the Z axis and the vector R where R begins at the origin and ends at some arbitrary observation point. The quantities R and θ are the usual polar angle and radius vector of the spherical coordinate system. Then

$$Z = R\cos\theta. \tag{5}$$

Equation (5) can be substituted in Eq. (4) to yield a potential function expressed in terms of R and θ. A useful expression can be obtained by letting $\theta = 0$ in this expression. This effectively replaces Z by R in Eq. (4).

The potential U also satisfies Laplace's equation. It is reasonable that the solution to this equation for the situation under consideration be cylindrically symmetric. Then an appropriate solution to Laplace's equation is[19]

$$U(R,\theta) = \sum C_n R^n P_n(\cos\theta), \quad 0 \leqslant n < \infty, \tag{6}$$

where n is an integer, the C_n's are arbitrary constants which are to be determined, and the P_n's are Legendre polynominals with $\cos\theta$ as their argument. R is the magnitude of R defined above. Now let $\theta = 0$ and used the fact that $P_n(\cos 0) = 1$ for all n, then the potential in Eq. (6) becomes

$$U(R,0) = \sum C_n R^n, \quad 0 \leqslant n < \infty. \tag{7}$$

The expression for U given in Eq. (4) with $Z = R$, and Eq. (7) represent the same function, so the coefficients of each R^n must be equal. The first few C_n's are found to be

$$Co = I/2, \quad C_1 = -I/2A, \quad C_3 = I/4A^3,$$
$$C_5 = -3I/16A^5, \quad C_7 = 5I/32A^7,$$
$$C_9 = -55I/256A^9, \quad C_{11} = 63I/512A^{11},$$
$$C_2 = C_4 = C_6 = C_8 = C_{10} = 0.$$

The above expressions for the C_n's and the appropriate expression for each Legendre polynomial[20] can be substituted into Eq. (6), giving the following approximate expression for U:

$$U(R,\theta) = [1 - R\cos\theta/A + R^3(5\cos^3\theta - 3\cos\theta)/4A^3 - 3R^5(63\cos^5\theta - 70\cos^3\theta + 15\cos\theta)/64A^5$$
$$+ 5R^7(429\cos^7\theta - 693\cos^5\theta + 315\cos^3\theta - 35\cos\theta)/256A^7$$
$$- 35R^9(12155\cos^9\theta - 25740\cos^7\theta + 18018\cos^5\theta - 4620\cos^3\theta + 315\cos\theta)/16384A^9]I/2. \quad (8)$$

Using Eq. (1) expressed in spherical coordinates, the components of the magnetic field are found to be

$$B_R(R,\theta) = [1 - 3R^2(5\cos^2\theta - 3)/4A^2 + 15R^4(63\cos^4\theta - 70\cos^2\theta + 15)/64A^4$$
$$- 35R^6(429\cos^6\theta - 693\cos^4\theta + 315\cos^2\theta - 35)/256A^6$$
$$+ 315R^8(12155\cos^8\theta - 25740\cos^6\theta + 18018\cos^4\theta - 4620\cos^2\theta + 315)/16384A^8]\mu_0 NI\cos\theta/2A, \quad (9a)$$

$$B_\theta(R,\theta) = [-1 + 3R^2(5\cos^2\theta - 1)/4A^2 - 45R^4(21\cos^4\theta - 4\cos^2\theta + 1)/64A^4$$
$$+ 5R^6(3003\cos^6\theta - 3465\cos^4\theta + 945\cos^2\theta - 35)/256A^6$$
$$- 525R^8(7293\cos^8\theta - 12012\cos^6\theta + 6006\cos^4\theta - 924\cos^2\theta + 21)/16384A^8]\mu_0 NI\sin\theta/2A, \quad (9b)$$

where the results for a single loop have been multiplied by N, the number of loops in the coil. The quantities of interest are the components of the magnetic field parallel to the Z axis (B_z) and perpendicular to the Z axis (B_r). These can be found from

$$B_Z = B_R\cos\theta - B_\theta\sin\theta,$$
$$B_r = B_R\sin\theta + B_\theta\cos\theta. \quad (10)$$

A computer program written in BASIC was used to calculate B_Z and B_r for both coils of the Helmholtz arrangement and then to combine the results to find the components of the total field at the desired point. A few results are given in Table I. In the region of interest the ratio of R to A is about 1/2. The last term in term in the series expansion in Eq. (9) contains the factor $(R/A)^8$ which is about 0.004 for $R/A = 1/2$. The factors which multiply the ratio R/A are all less than unity so the $(R/A)^8$ term amounts to less than 0.4% of the leading term. This indicates that for the accuracy desired in this work that enough terms were used in the calculations.

To check the computations using Eqs. (9) and (10), the field was calculated for a point on the Z axis halfway between the coils for $I = 1.0$ A. For the apparatus used, $A = 0.33$ m and $N = 72$ turns. This gave values of $B_z = 1.968\times10^{-4}$ T and $B_r = 0.000$ T. The formula for the magnetic field at the center of the Helmholtz coil configuration is usually given as[21]

$$B_Z = 8\mu_0 NI/A\,5^{3/2}. \quad (11)$$

Using this formula B_Z was calculated as 1.962×10^{-4} T.

Table I. Components of the calculated magnetic field for a current of 1.0 A.

R_1 (m)	z (m)	$B_z\times10^4$ (T)	$B_r\times10^7$ (T)
0.00	0.000	1.968	0.000
0.05	0.000	1.959	0.000
0.05	0.005	1.959	1.270
0.05	0.010	1.959	2.595
0.05	0.015	1.960	4.033
0.05	0.020	1.960	5.642
0.05	0.025	1.961	7.490
0.05	0.030	1.961	9.649
0.05	0.035	1.962	12.20

Thus the approximate expression and the exact expression agree quite well. As can be seen from Table I, the magnetic field at the electron's path is not significantly different from that at the center. This answered the student's first question.

The perpendicular component of the field was calculated in order to see if it contributed to making the beam fan shaped. It did not cause a significant amount of the spreading. The cause of the beam spreading is discussed in the next section.

IV. ELECTRON MOTION IN THE SOURCE

The source of the electrons is a straight wire of radius r_i carrying a current i in the $-z$ direction, which heats the wire to a temperature sufficient for electron emission. The wire has an electric potential of zero. A thin conducting cylinder with a potential V is concentric with the wire and the inside radius of the cylinder is r_f. The cylinder has a narrow slit cut in part of its surface. The slit is parallel to the axis of the cylinder and the wire. The slit, r_i and r_f are indicated in Fig. 2. The electrons will be accelerated towards the cylinder and a few will pass through the slit to form the beam that is bent by the magnetic field of the Helmholtz coils. The long dimension of the slit is parallel to B_Z and the z axis. Let the $x-y$ plane be midway between the Helmholtz coils and the origin at the axis of the heated wire. The slit will then extend from $-z_0$ to $+z_0$. By symmetry, the motion below $z=0$ will be the mirror image of the motion above $z=0$, so only the case of $z>0$ will be considered. The electrons going through the slit at $z=z_0$ will form the upper edge of the fan. Therefore, only the motion of these electrons will be considered. The current flowing in the hot wire will also cause a magnetic field that is cylindrically symmetric around the wire. The electrons are accelerated radially away from the wire by the electric field between the wire and the cylinder. Thus they will be moving in a direction perpendicular to the wire's magnetic field. By the Lorentz force law, a force will be exerted on the electrons in a direction parallel to the z axis. The wire was heated by an alternating current of 60 Hz, so the force will vary with time. It is this force that causes most of the spreading of the beam into the fan shape. To calculate the electron's motion along the upper edge of the fan, the maximum current needs to be used. The maximum is obtained from the rms value indicated by the ammeter which was connected in the hot wire circuit.

Table II. Spreadsheet results for half-height calculations.

n	Time (ns)	$a_z \times 10^{-11}$ (ms^{-2})	$v_z \times 10^{-5}$ (ms^{-1})	z (m)	L (m)
0	0.0	5.50	8.20	0.005	0.000
1	2.65	8.00	8.21	0.007	0.016
2	5.30	10.6	8.23	0.009	0.031
3	7.95	13.2	8.26	0.012	0.047
4	10.6	15.7	8.30	0.014	0.063
5	13.3	18.3	8.34	0.016	0.079
6	15.9	21.0	8.40	0.018	0.094
7	18.6	24.0	8.45	0.020	0.11
8	21.2	27.3	8.51	0.023	0.13
9	23.8	30.8	8.58	0.025	0.14
10	26.5	34.5	8.66	0.027	0.16

The velocity of the electrons in the z direction as they leave the slit will now be calculated. To simplify the calculations, the field due to the Helmholtz coils will be neglected so that the motion of the electrons in the source can be approximated as occurring in a plane determined by the axis of the heated wire and the slit. The coordinate system will be chosen so that the x axis goes through the slit and the angle ϕ will be in the $x-y$ plane measured from the x axis. The location of a point will then be given by the cylindrical coordinates (r,ϕ,z). Combining $F = ma$ with the Lorentz force law, we have $m\mathbf{a} = q(\mathbf{E} + \mathbf{v}\times\mathbf{B})$. Let

$$q = -e, \quad \mathbf{E} = -\alpha\hat{\mathbf{r}}/r, \quad \mathbf{B} = -\beta\hat{\boldsymbol{\phi}}/r,$$

where

$$\alpha = V[\ln(r_f/r_i)], \quad \beta = \mu_0 i/2\pi,$$

$$\hat{\mathbf{r}} = \hat{\mathbf{i}}\cos\phi + \hat{\mathbf{j}}\sin\phi, \quad \hat{\boldsymbol{\phi}} = \hat{\mathbf{i}}\sin\phi + \hat{\mathbf{j}}\cos\phi.$$

Putting the above expressions for E and B in this equation, and expressing a and v in cylindrical coordinates, we find

$$m(\ddot{r} - r\dot{\phi}^2) = e(\alpha/r - \beta\dot{z}/r) \quad r \text{ component}, \tag{12a}$$

$$m(r\ddot{\phi} + 2\dot{r}\dot{\phi}) = 0 \quad \phi \text{ component}, \tag{12b}$$

$$m\ddot{z} = e\beta\dot{r}/r \quad z \text{ component}, \tag{12c}$$

for the three components of motion where the dots indicate time derivatives. If Eq. (12c) is rewritten as

$$m\dot{v}_z = e\beta[d(\ln r)/dt] \tag{12c}$$

and integrated, then

$$mv_z = e\beta[\ln(r)] + K. \tag{13}$$

If it is assumed that $v_z = 0$ at $r = r_i$, K can be evaluated and its value put in Eq. (13) giving

$$v_z = [\ln(r/r_i)]e\beta/m. \tag{14}$$

The specification sheet accompanying the apparatus gave r_i as 1.0×10^{-4} m and r_f as 6.4×10^{-3} m. Letting $r = r_f$ and $i = 5.7$ A, which was the peak value of the current used by the students, $v_z = 8.2\times10^5$ ms^{-1}. After leaving the slit the electrons traveled in a path that was primarily circular with the circle being nearly parallel to the $x-y$ plane. The current in the Helmholtz coils was adjusted so that the electrons hit an indicator which was about 0.1 m from the axis of the hot wire. Hence the electrons traveled about 0.15 m along the circumference of a circle of radius 0.05 m. However, the trajectory of the electrons had a small component of motion normal to the planes of the Helmholtz coils, and this caused the beam to be fan shaped. To make a rough calculation of the spreading, the following expressions were used:

$$v_{n+1} = v_n + a_n\Delta t,$$
$$z_{n+1} = z_n + v_n\Delta + a_n(\Delta t)^2/2. \tag{15}$$

A spreadsheet program was used to carry out the calculations, and the results are given in Table II. The magnitude of the velocity of the electrons in a direction perpendicular to the source can be calculated from $eV = mv_r^2/2$. The accelerating voltage V used in this experiment was 100 V. This gives a value of 5.93×10^6 ms^{-1} for v_r. Since v_r is about seven times larger than the component of the velocity along the source axis, it is assumed that the speed to be used in calculating the electron's acceleration in the direction along the source axis can be taken as v_r. The direction of the source axis is in the same direction as the axis of the Helmholtz coils and is also the direction in which the beam's rectangular cross section increases. From $evB_r = ma_z$, a_z can be found for the values of B_r listed in Table I for $R_1 = 0.05$ m. A graph of a_z vs z was made, but not shown here, then the average value of a_z in the interval z_n to z_{n+1} was used in the spreadsheet calculations. The time for the electrons to travel through a semicircular arc was calculated by dividing the arc length ($\pi\times0.05$ m) by $v_r = 5.93\times10^6$ ms^{-1}. This gave 26.5 ns. The calculations were done for ten values at increments of 2.65 ns. It was felt that ten intervals were sufficient for this experiment. The spreadsheet program allowed for an iteration approach to be used, and two iterations per time increment were sufficient.

A measurement of the half-height z of the fan at a distance $L = 0.09$ m along the circumference gave a value of 0.018 m. This is in excellent agreement with the calculated value given tn Table II for the $n = 6$ calculated half-height. Therefore, it is felt that the students second question has also been answered.

That the B_r component of the magnetic field had a negligible effect on the half-height z calculation can be shown by considering the last line in Table II. At this point B_r is the greatest and would have the largest effect. However, if the initial speed v_z of 8.2×10^5 ms^{-1} is multiplied by 26.5 ns, the time that is took the electrons to traverse the semicircle, and added to the initial displacement of 0.005 m, z is found to be 0.027 m. Comparing this value to the last half-height of 0.027 m given in Table II, it can be seen that the force due to B_r contributes a negligible amount to the calculated displacement at the end of the path. At intermediate points the effect is less. The relatively small change of the speed v_z shown in Table II also indicates that B_r has a small effect on the half-height. Hence, as stated at the end of Sec. III, the B_r component of the magnetic field does not cause a significant amount of the beam spreading.

ACKNOWLEDGMENTS

I am indebted to Donald Allen and Michael Boerner for asking the questions which instigated this project and who provided the experimental data cited in this article.

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In memoriam J. Jaumann: A direct demonstration of the drift velocity in metals

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Moving a Hall specimen perpendicular to the magnetic field and in the opposite direction to the drift motion of carriers with exactly the drift velocity results in a compensation of the Hall voltage. Thus a drift velocity of, e.g., 0.6 mm s^{-1} in Cu can be directly observed.

INTRODUCTION

Electrical signals in metal conductors spread almost at the speed of light, whereas the average velocity of electrons involved in signal propagation is much slower. Even to physics students who are used to describing signal propagation in terms of waves in an incompressible gas, the fact that the drift velocity of electrons in, for example, copper is as low as a fraction of a millimeter per second, is quite astonishing.

Nearly every student of physics has seen the demonstration of ionic conduction in liquids. Here one can observe the slow motion of colored ions in an electric field. With electrons in metals a visual demonstration cannot be performed so easily.

In a collection of short notes on lecture demonstrations left by the late J. Jaumann[1] professor emeritus of physics at the University of Cologne, an experiment is described which allows for a visual observation of the drift velocity in metals. The experiment is based upon the compensation of the Hall voltage in a metal specimen by moving it relative to the magnetic field. If this motion is carried out so that the velocity of the drifting electrons is zero with respect to the magnetic field, the Hall voltage vanishes as the specimen moves with exactly the drift velocity in the opposite direction.

EXPERIMENT

The Hall specimen is mounted on a spindle driven by a gear motor and can thus be moved at variable speeds between the 5-mm air gap of an electromagnet. The specimen consists of a 17-μm-thick Cu foil 120 mm long and 40 mm wide backed by a thin sheet of glass fiber epoxy which carries the current contacts and the Hall contacts.

Figure 1 shows the arrangement with contacts *a* and *b* located so that the opposing contact *c* is electrically between *a* and *b*. This allows for the compensation of a geometrical mismatch causing a voltage drop between Hall contacts when current is passed through the specimen without the magnetic field being switched on.

The main current is about 10 A. The Hall specimen can be moved with speeds up to 2 mm/s. With 30-mm-diam pole faces spaced about 5 mm apart, the magnet can supply a field of 1 T giving rise to a Hall voltage of about 30 μV.

With a current of 10 A through the specimen and the magnet switched off, the position of the virtual contact between *a* and *b* is adjusted with the compensation potentiometer *R* so that the voltage across the amplifier input ter-

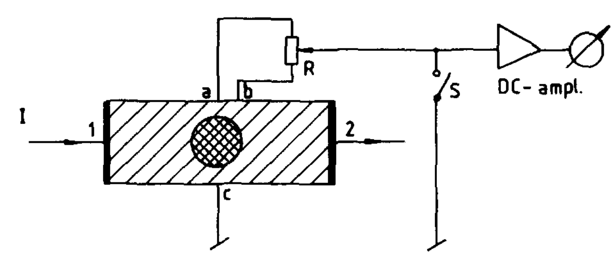

Fig. 1. Hall specimen with compensation contacts *a* and *b* 15 mm apart. The main current contacts 1 and 2 are fastened to the foil by 1-mm-thick copper bars. The shaded area indicates the pole face area of the magnet. *S* is used to protect the amplifier when the magnet is switched on.