IV.—MISCELLANEOUS.

Art. LIX.—*Magnetization of Iron by High-frequency Discharges.*

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Plates XLVIII. and XLIX.

I. Magnetization of Iron by Leyden-jar Discharges.

The subject of the magnetization of iron in very rapidly-varying fields has been touched upon more or less fully by several different scientists, notably Dr. Lodge, Professor J. J. Thomson, Hertz, and a few others. In Dr. Lodge's "Modern Views of Electricity" we find the following: "But in the case of a discharge of a leyden-jar iron is of no advantage. The current oscillates so quickly that any iron introduced into the circuit, however subdivided into thin wires it may be, is protected from magnetism by inverse currents induced in its outer skin, and accordingly does not get magnetized, and, so far from increasing the inductance of the discharge circuit, it positively diminishes it by the reaction effect of these induced currents; it acts, in fact, much as a mass of copper might be expected to do."

In Fleming's "Alternate Current Transformer," vol. i., p. 398, there is a description of Dr. Lodge's experiments on the effect of iron in rapidly-varying fields: "With respect to the apparent superiority of iron, it would naturally be supposed that, since the magnetic permeability of iron bestows upon it greater inductance, it would form a less suitable conductor for discharging with great suddenness electrical energy. Owing to the fact that the current only penetrates into the skin of the conductor there is but little of the mass of the iron magnetized, even if these instantaneous discharges are capable of magnetizing iron . . . the electro-motive impulses, or sudden rushes of electricity, do not magnetize the iron, and hence do not find in it greater self-inductance than they would find in a non-magnetic but otherwise similar conductor."

Dr. Hertz, from his experiments on oscillating circuits, came to the conclusion that iron was not magnetic for very rapid frequencies; and, to quote from Fleming's abstract of Hertz's researches (vol. i., p. 416), "Hertz supposed that, as the self-inductance of iron wires is for slow alternations from eight to ten times that of copper wires, therefore a short iron wire would balance a long copper one; but this was not found to be the case, and he concludes that, owing to the great rapidity of the alternations, the magnetism of the iron is unable to follow them, and therefore has no effect on the self-induction." And again, p. 423: "When the wire was surrounded by an iron tube, or when it was replaced by an iron wire, no perceptible effect was obtained, confirming the conclusion previously arrived at that the magnetism of the iron is unable to follow such rapid oscillations, and therefore exerts no appreciable effect."

Steefan has, however, shown that we could expect very little alteration in the inductance of a wire, even if it were magnetic, on account of the greater concentration of the current in a magnetic conductor on the surface of the wire.

Professor J. J. Thomson ("Recent Researches," p. 322, and "Philosophical Magazine," 1891, p. 457) has shown that an iron cylinder placed in a solenoid absorbs considerably more energy than a similar non-magnetic conductor of equal conductivity, on account of the higher permeability of the iron.

J. Trowbridge ("Damping of Electric Oscillations": Phil. Mag., December, 1891) has shown that the resistance of iron wires damps electrical energy very considerably, and has deduced that iron must have a fairly high permeability to account for the effects observed.

Lastly, we have the statement, in the last page of Gray's "Absolute Measurements," that the damping of oscillations in a resonator is greater when the wire is of iron than when it is of copper.

In order to investigate the effect of "magnetic penetration" in iron for fields varying very much more rapidly than could be obtained with the use of the "time apparatus," the readiest means to hand for obtaining a very rapid oscillatory current was the ordinary leyden-jar discharge.

The subject of the magnetization of iron in these fields has been very little touched upon since the time that Henry experimented on the effect of leyden-jar discharges on the magnetization of steel needles.

In the experiments that follow it will be shown that iron is strongly magnetic in rapidly-varying fields, even when the frequency is over 100,000,000 per second.

A solenoid was wound on a small glass tube, sixty turns of wire, seven turns to the centimetre. A leyden-jar, charged up to a convenient potential by a Voss machine, discharged through this solenoid, and any iron, whether solid or finely divided, placed inside the solenoid was always more or less magnetized by the discharge.

Plate XLVIII., Fig. 1.

C, ordinary leyden-jar; A is solenoid; S, spark-gap.

The whole of the discharge passed through solenoid A. After the discharge had passed the needles were examined by means of a small mirror magnetometer. As this magnetometer is used in all future experiments for testing the magnetization of needles, the construction is briefly explained. It was made on the pattern set forth in Gray's "Absolute Measurements," vol. ii., p. 79. The needle was small, and arranged in a cavity, so that it was nearly dead-beat. The deflection was increased by means of a lamp and scale in the ordinary way. The value of the horizontal component at the needle was 0·22, and remained practically constant, as there were no masses of iron in the vicinity.

It was first settled that the needle placed in the solenoid was unaffected by the charging current from the Voss. The Voss was turned so as to charge up the jars just below the potential necessary to spark across knobs at S. The needle was then removed and tested by the magnetometer. No effect was observed.

The effect of discharges on needles of different diameters was first investigated. Length of needles, 7cm.:—

(1.) Part of steel knitting-needle, diameter 0·103in.: Deflection 112, at 9cm. distance from magnetometer needle.

(2.) Pianoforte steel wire, diameter 0·032in.: Deflection, 40; distance from magnetometer, 9cm.

(3.) Thin steel wire, diameter 0·008in.: Deflection, 10; distance from magnetometer, 9cm.

Diameter.	Deflection.
0·103in.	112
0·032in.	40
0·008in.	10

It will be observed from these experiments that the deflection is very nearly proportional to the diameter of the wire. This is to be expected, as the magnetizing forces are confined to a thin skin of the substance. The amount of the magnetization of the wire is proportional to the surface of the iron, and not to its sectional area, as it is for steady currents. In order to show that the effect was a surface one, and did not penetrate any depth, a cylinder of thin copper was placed over the needle. The needle gave no appreciable deflection, showing that the copper cylinder completely screened off any effect on the iron. A thin external iron cylinder gave the same effect.

In order to determine with accuracy the state of a needle which had been under the influence of discharge, recourse was had to a method of solution of the iron. After several preliminary experiments, dilute HNO_3 at a temperature of boiling water was found to give the most reliable results. In order to test the rate at which the iron was eaten away a piece of pianoforte-wire 6·5cm. long, 0·032in. diameter, was taken and placed inside a solenoid, and subjected to a steady field of 100 C.G.S. units. The needle was then assumed to be magnetized uniformly throughout its section.

Plate XLVIII., Fig. 2.

E H F is a glass vessel, inside another glass vessel, A B C D, which is supported on a tripod of copper. Water is kept boiling in the outer vessel by a burner, K. Inside the inner vessel, but not touching it, is the needle, firmly fixed by the ends in a light frame. This frame is supported clear of the vessels by the stand, S.

The needle is fixed horizontally at a distance from the magnetometer, R, to give a convenient deflection on the scale. As the water is heated up to boiling-point the deflection due to the needle decreases slightly, due to the effect of temperature on the magnetic moment of the needle.

At a stand alongside, the dilute HNO_3 is kept in a beaker of boiling water, and when all is ready the HNO_3 is quickly transferred to the vessel E H F, taking care not to disturb the needle. The moment the HNO_3 reaches the level of the needle in the vessel the time is noted, for at that instant the needle commences to dissolve. Sufficient HNO_3 is poured in to cover the needle half an inch.

As the needle is dissolved the deflection falls, and the deflection at different intervals is carefully noted.

This method of fixing the needle first and then pouring in the acid was unavoidable, as the maximum deflection due to the needle could not otherwise be obtained. By keeping the HNO_3 at 100° C. and rapidly transferring it to the vessel (itself surrounded by boiling water) we insure that the needle is covered by HNO_3 at the same temperature during the whole time of solution. Since the amount of acid was large compared with the size of the needle, the effect of solution of the iron would not materially alter the rate at which the needle was dissolved.

A uniformly-magnetized steel needle was found to dissolve very regularly till it was reduced to an extremely fine filament, which did not break up until the magnetometer deflection had fallen within 3 div. of zero. The following is the result of an experiment on a uniformly-magnetized needle (needle 0·032in. in diameter; steady deflection just before acid is poured in = 222):—

Time in Seconds after Solution begins.	Deflection.
0	222
30	217
49	195
56	177
90	157
115	147
139	137
206	107
246	97
311	77
373	57
414	47
454	37
566	17
638	7

It would be expected that the rate of solution of the metal at any instant would be : :$^{\text{al}}$ to the surface of the metal at that instant—that is, to the radius of the wire. This is very accurately the case in the above experiment. The deflection of the magnetometer at any instant is proportional to the sectional area of the wire—*i.e.*, to the square of the radius. The radius of the wire at any moment is therefore known.

If a curve is constructed whose abscissæ represent time, and ordinates the radii of the wire at different intervals, it will be found to be nearly a straight line, with the exception of an irregularity in the beginning of the curve.

A needle of steel 0·032 in. diameter was then taken, and magnetized by passing the discharge from four leyden-jars in parallel through the solenoid. Spark-length, $\frac{1}{10}$in. A correction was made for the fall of deflection when needle was immersed in dilute HNO_3 at 100° C.

Plate XLVIII., Fig. 3.

The following is the table of observed values of time and deflection. The values of time and deflection are reduced for convenience in plotting curves:—

Abscissæ.	Ordinates.
0·0	8·5
0·7	12·5
1·7	14
3·2	15
4·2	15·3
5·2	15·6
6·2	15·5
7	15
8	14
9·2	12
10·5	10
11·7	8
12·9	6
14·4	4
16·2	2
18·2	1
20·2	0·5

The steady deflection at first was 85. As the iron commenced to be eaten away the deflection rapidly rose, and reached its maximum, 156. It remained stationary for a short interval at its maximum value, and then rapidly decreased down to zero. When the deflection had fallen to zero the needle was removed, its diameter measured, and found to be 0·013in. The depth of magnetic penetration was therefore about 0·0095in.

Now, from the results of experiments on the eating-away of uniformly-magnetized needles, we see that the depth to which the iron is dissolved is proportional to the time. Since in 200sec. the depth dissolved was 0·0095in., the rate of solution = 0·000047in. per second.

If I represent intensity of magnetization of a thin circular shell, distance r from centre of the needle, and M the deflection of the magnetometer at any instant,—

Then $\int I \cdot 2\pi r \cdot dr$ is $::^{\text{al}}$ to M;

$\therefore\ I \cdot r$ is $::^{\text{al}}$ to $\frac{dM}{dr}$.

If a be radius of needle at first, it has been shown that $(a - r)$ is $::^{\text{al}}$ to t (the time of action of acid).

Let $a - r = k \cdot t$,
then $-dr = kdt$,
and, substituting in equation (1), we get—

$I\,(a - kt)$ is $::^{\text{al}}$ to $\frac{dM}{dt}$, since dr is $::^{\text{al}}$ to dt;

$\therefore$ I is $::^{\text{al}}$ to $\frac{1}{a - kt} \cdot \frac{dM}{dt}$.

Now, $\frac{dM}{dt}$ is the value of the tangent of the angle that the tangent at any point of the curve B (see Plate XLVIII., Fig. 3) makes with the axis of abscissæ. $\frac{dM}{dt}$ is ∴ known from curve B. We can consequently determine the curve of variation of I from the surface to the centre, although there are not sufficient data to actually calculate I in absolute measure.

Plate XLVIII., Fig. 4.

The curve in Fig. 4 is an approximate representation of the magnetization from the surface inwards. The ordinates represent I, the intensity of magnetization. The abscissæ represent the distances from the external surface of wire.

It will be observed that the surface-layer is magnetized in an opposite direction to the main part of the magnetized metal.

As we go inwards from the surface the intensity of magnetization rapidly decreases till at the point A there is a portion of the metal which is not magnetized. This will be called the "neutral point."

On penetrating still further the magnetization changes sign, and rapidly rises to a maximum, which most probably represents an intensity corresponding to the saturation-point of steel. The intensity then remains practically constant till at D it decreases very rapidly down to zero.

It is evident from the manner in which the magnetization varies inwards that the iron has been under the influence of an oscillatory discharge. The first half-oscillation penetrated to a depth of $\frac{1}{100}$in., which is represented by the length O B in the figure. The neutral point A is at a depth of about $\frac{1}{400}$in. from the surface. The second half-oscillation has evidently decreased in amplitude considerably, since the depth of penetration is only a quarter that of the first discharge.

In this experiment there is only evidence of two half-oscillations. Several needles were examined which had been magnetized under the influence of various fields and different lengths of spark-gap, but the existence of the return oscillation could not with certainty be detected.

All the needles used gave the same general result—viz., a thin surface-layer magnetized in one direction, and a thicker interior layer magnetized in the opposite direction.

In one case examined the depth of penetration of the first discharge was considerably less than $\frac{1}{1000}$in.

The effect of varying the capacity of the condenser and keeping the self-inductance and the spark-gap constant was also investigated.

In the first experiment four leyden-jars were placed in parallel; the depth of penetration was found to be $\frac{1}{100}$in.

In next experiment two leyden-jars were placed in series; the depth of penetration was found to be 0·0035in.

$\therefore$ in first case discharge penetrates 2·8 times the distance of the second case. But the capacity in the first case was eight times that in the second case; $\sqrt{8} = 2{\cdot}8$, and therefore from this experiment we see that the depth of penetration is $::^{\mathrm{al}}$ to the square root of the capacity.

But from the equation of discharge of leyden-jar of capacity C through inductance L the maximum current is given by

$$j = \frac{CV_0}{(LC)^{\frac{1}{2}}} e^{-\frac{R}{2L} \cdot t},$$

where V_0 is potential of charge, and R resistance in circuit.

The maximum current varies therefore as $\sqrt{C}$. The depth of penetration is therefore $::^{\mathrm{al}}$ to the maximum current.

II. Effect of Continued Discharges on the Magnetism of a Needle.

It was observed that the magnetization of a needle was increased by sending a large number of discharges in one direction. In all the experiments that follow, a uniformly-magnetized steel needle was used, and the effect of a discharge in decreasing the deflection due to the needle was observed. A uniformly-magnetized needle has many advantages over an ordinary unmagnetized needle. These advantages need not be discussed at this point, for they will be sufficiently obvious as the paper proceeds.

A solenoid of a large number of turns was wound, and a battery current sent through it sufficient to produce a field of over 100 C.G.S. units in the solenoid. The steel needle was thus practically saturated when required by placing it in the solenoid and turning on the current.

Plate XLVIII., Fig. 5.

The condenser is charged by Voss or induction machine. In most of the later experiments an induction coil was used.

A B is a solenoid of about three turns per centimetre placed behind magnetometer. The needle was first saturated, and then placed in solenoid A B at such a distance from the magnetometer as to give a convenient deflection. When a spark occurred at S the deflection due to needle in A B fell. It was observed that the effect on the needle did not end with the first discharge, but the deflection fell gradually for every spark that passed, till finally the iron reached a steady state, and there was no further change of deflection, however many sparks were passed.

There was also a marked difference between the effects produced by discharges in opposite directions on the same saturated needle.

(1.) When the first half-oscillation tended to magnetize the needle in the same direction as it already was magnetized the first half-oscillation had no effect on the needle, it being already saturated. The second half-oscillation tended to demagnetize the needle, the third to magnetize it, and so on.

As an example of the effect of continued sparks in this direction we have the following:—

No. of Sparks.	Steady Deflection.
0	252
1	226
2	217
Several sparks	210

(2.) When first half-oscillation tended to demagnetize the needle the effect on the reduction of the deflection is much greater; for example:—

No. of Sparks.	Steady Deflection.
0	252
1	156
2	102
3	83
4	67
5	54
6	45
9	25
10	15
20 sparks	10

The deflection did not fall below 10 div., however many sparks were passed. The iron has then arrived at the steady state. The gradual demagnetization of iron by successive discharges is well illustrated by the above table. The cause of the effect was not at first clear, but further experiment showed that it was due to the very rapid damping of the oscillations. The first oscillation demagnetizes the surface-layers, and probably magnetizes a thin surface-shell to saturation in the opposite direction. The second half-oscillation wipes out some of this opposing magnetism, but to no appreciable depth, since the amplitude of the oscillation is by that time greatly reduced. The third half-oscillation tends to magnetize the iron again, and so on.

When another discharge is passed through the solenoid the first half-oscillation has first of all to demagnetize and magnetize the surface-layers in opposite direction to magnetism of needle. When it has penetrated through the thin surface-shell the magnetic force meets with a layer of iron of low permeability, since the greater part is already magnetized nearly to saturation in the same direction by the action of the first half-oscillation of the first discharge. It therefore penetrates further, for we know the magnetic force penetrates deeper in a conductor like copper ($\mu=1$) than in a conductor like iron, where μ may be considerable. More iron is demagnetized and the deflection reduced. This continues as spark after spark is passed, till finally the discharge cannot penetrate any further. This corresponds to the steady state. It was found, by dissolving a needle acted on in this way by a succession of discharges, that the deflection rose steadily as the needle was eaten away, showing that the surface-layer was magnetized in an opposite direction to the central part.

In the experiment above detailed it was found that the discharge had penetrated to about one-quarter of the radius—*i.e.*, a distance of 0·008in. When thin steel needles were experimented on they were often totally demagnetized and magnetized in the opposite direction by successive discharges: *e.g.*, thin steel needle, 0·008in. diameter:—

(1.) Effect of second half-oscillation and succeeding—

Sparks.	Deflection.
0	150
1	80
2	55
3	50 &c.

(2.) Effect of first half-oscillation and succeeding—

Sparks.	Deflection.
0	150
1	−15
2	−120
3	−140

Soft iron as well as steel needles exhibited the same effect.

The difference between the effect of the first and the second half-oscillation in demagnetizing iron is very marked. The experiments show clearly how rapidly the oscillations decay in amplitude. When we are dealing with capacities of about 1,000 electrostatic units and small inductance in the circuit it seems very probable that there is only one complete oscillation. The others are damped down to such an extent as to be inappreciable. The fact that the deflection due to the needle always falls, whatever the direction of the first oscillation, shows clearly that the discharge is oscillatory. If there was only a unidirectional discharge the needle should only be affected when the discharge is in one direction.

Simple experiments of this nature on ordinary steel needles show that a leyden-jar discharge is oscillatory, and show also the rapid decay of the amplitude of the vibrations.

A method of deducing the ratio of the second half-oscillation to the first will be given later.

The subject of the decay of amplitude of the vibrations of a leyden-jar discharge is of considerable interest, especially in connection with the resistance of spark-gaps and the radiation of energy into space.

Let L = self-inductance of discharge circuit for rapid alternations;
C = capacity of condenser;
V_0 = potential of jar;
R = resistance of connections and spark-gap to the discharge.

Then the current j at any instant is given by

$$j = \frac{CV_0}{(LC)^{\frac{1}{2}}} e^{-\frac{R}{2L}\cdot t} \sin. \frac{t}{(L\,C)^{\frac{1}{2}}}.$$

The exponential factor only includes the case of frictional dissipation of energy, and does not take into account radiation into space. In the experiments at present considered, where the condenser is a leyden-jar, the lines of force of which pass from one coating to the other, there can be a very small amount of dissipation of energy due to radiation ("Recent Researches," J. J. Thomson, p. 482). We can obtain a fairly accurate estimate of the decay of amplitude of the vibrations from the experiments of eating away of needles by HNO_3, but a more useful estimate may be obtained from considerations of the loss of magnetism of a needle as determined by a magnetometer.

Two small oppositely-wound solenoids, A and B, were placed in series connecting the coatings of an ordinary leyden-jar discharging through a spark-gap of $\frac{1}{10}$in. Two steel needles similar in all respects and magnetized to saturation were taken and placed in the solenoids A and B, so that their north poles faced in the same direction.

Plate XLVIII., Fig 6.

When the leyden-jar was discharged through the spark-gap the first half-oscillation tended to magnetize the needle in A to a greater extent; but, as it was practically saturated, no effect was produced. The second half-oscillation tended to demagnetize the needle, the third half-oscillation to magnetize it again, and so on.

On the needle in B, however, the first half-oscillation produced its full effect in demagnetizing, the second half tending to magnetize again, and so on.

On needle in A: First, third, fifth, seventh, &c., half-oscillations tend to magnetize needle in original direction; second, fourth, sixth, eighth, &c., tend to demagnetize needle.

On needle in B: Second, fourth, sixth, &c., tend to magnetize needle; first, third, fifth, &c., tend to demagnetize needle.

Now, the strength of field H in a solenoid of length large compared with its radius is given by

$$H = 4\pi nc$$

when n is number of turns per centimetre.

Now, suppose that the solenoids A and B are of the same number of turns per centimetre. Then the needle in B, since it is acted on by the first half-oscillation, will be demagnetized to a greater extent than the needle in A. The fall of the deflection in every case was readily determined by the small mirror magnetometer.

Let the number of turns per centimetre on solenoid B be reduced until there is exactly the same fall of deflection in each needle after one discharge. The maximum magnetizing force on needle in A = $4\pi nc$, where c is maximum current of second half-oscillation; the maximum magnetizing force on needle in B = $4\pi n'c'$, where n' = number of turns per centimetre, and c' = maximum current of first half-oscillation.

Now, since the effects on the needles are identical in the two cases, and the period is the same for both, the maximum magnetizing forces in the two solenoids must have been equal.

$$\therefore 4\pi nc = 4\pi n'c'.$$

$$\therefore \frac{c}{c'} = \frac{n'}{n},$$

or the maximum currents of the two half-oscillations are to one another inversely as the number of turns per centimetre on solenoids. There is, of course, an assumption here that the effect on the needles is $: :^{\mathrm{al}}$ to maximum magnetizing force when the period is constant. Experimentally it was found that the depth of penetration of magnetic force was $: :^{\mathrm{al}}$ to the maximum current ordinate when period was constant, and the assumption made is a very close approximation to the truth.

The connection between the depths of penetration when the periods varied was more complicated, and not expressed by any simple law.

In experimenting it was found advantageous to pass about twenty discharges instead of one, as the depth of penetration was greatly increased, and also the action of the first effective oscillation was in a great measure differentiated from the effect of the secondary ones.

Many experiments on the relation between the amplitudes of the first and second half-oscillations were made under varying conditions. A few of these are incorporated in a "Note on the Resistance of Spark-gaps," placed at the end of this paper.

The general result obtained was that for a spark-gap of $\frac{1}{10}$in., and inductance of about 4,000 C.G.S. units in circuit, the amplitude of the second half-oscillation was less than half that of the first.

As an example of a balance of the kind explained, when 2·15 turns per centimetre were on the one solenoid and 1·06 turns per centimetre on the other the effect on the needles was exactly equal.

$$\therefore \left.\frac{\text{amplitude of second half-oscillation}}{\text{amplitude of first half-oscillation}}\right\} = \frac{1 \cdot 06}{2 \cdot 15} = 0 \cdot 493,$$

or nearly one-half.

If this rate of decay holds for succeeding oscillations the return oscillation has only one-quarter of maximum value of first oscillation.

Plate XLVIII., Fig. 7.

The curve in Fig. 7 is a rough representation of the rapid decay of the oscillations. If the rate of decay continues for several oscillations the current will have a very small fraction of its original maximum value. It has been shown how a magnetized steel needle placed in a small solenoid may be used as a detector of an oscillatory discharge, and also as a means of determining the rate of decay of the oscillation.

A series of different experiments was then undertaken to show that iron possesses magnetic properties under the influence of all kinds of discharges.

The needle was placed in a solenoid connecting the external coatings of leyden-jars A and B, arranged as in Lodge's experiments on the "alternate path."

Plate XLVIII., Fig. 8.

A and B are two leyden-jars connected in series through the solenoid D. When a spark occurs at C there is an impulsive rush of electricity through the solenoid D. The steel or soft-iron wire placed in the solenoid exhibited the same effect as when the discharge occurs in the ordinary way. The wire was always demagnetized, and the loss of magnetism was almost exactly the same as when the jars are connected in series in the ordinary way and discharged. There was the same rate of decay of amplitude also, and, as far as regards the effect on magnetized needles, the impulsive discharge is of the same nature as the ordinary discharge.

(2.) The needle was next placed in a small solenoid in series with one of the long wires reaching from the coatings of the condenser, as in Lodge's experiment on the velocity of electric radiation.

Plate XLIX., Fig. 9.

BD, TF, were a pair of wires, each about 20 yards long, leading from the condenser. This length was timed as far as possible to be in unison with the discharge at A: *i.e.*, the length of one of the wires was half a wave-length. With $\frac{1}{10}$in. spark at A, a spark of $\frac{3}{4}$in. could be obtained at spark-gap D, and the ends gave off a beautiful glow discharge every time a spark occurred at A.

The deflection of the needle always fell in value after a discharge, and there was not such a difference between the amplitude of the first and the second half-oscillation as in the previous cases.

With discharge in one direction deflection fell from 310 to 250; with discharge in opposite direction deflection fell from 300 to 255: showing that the first and second half-oscillations do not differ much in amplitude.

It seems very probable that when the long wires are timed in unison with the discharging current the rate of decay of vibrations in the long wires is independent of that of the discharging circuit. The long wires act as a resonator, and oscillate long after the oscillations in the vibrator have ceased. It made very little difference in the effect on the needle whether the knobs at the ends of the long wires were close together or far apart. To magnetize iron in rapid fields a closed circuit is not required. Another example of this will be given later.

From this and the previous experiment we see that iron is magnetic under the influence of impulsive rushes of electricity.

III. EFFECT OF INDUCED SECONDARY CURRENTS ON THE MAGNETIZATION OF IRON.

Plate XLIX., Fig. 10.

A primary coil of ten turns of insulated wire was placed inside a glass tube, and a secondary of twelve turns outside the tube. A discharge was passed through the primary, and induced currents obtained in the secondary, giving a small spark at B. When a magnetized steel needle 0·032 in diameter was placed in a solenoid of three turns to the centimetre the deflection fell from 300 to 261.

In order to see the effect of resistance on the amount of current in the secondary, 10 yards of platinoid wire was placed in series with the secondary. Deflection fell from 300 to 285.

On removing platinoid wire and placing a copper wire of same length and section in its place very little difference in the deflection was observed, although resistance of platinoid wire was 130 ohms and of the copper not more than 3 ohms. This shows that the quantity that flows in the secondary is practically independent of the resistance of the conductors.

This agrees with the theory; for if M be the coefficient of mutual induction between the two coils, and I self-induction of secondary, then the quantity of electricity circulating in the secondary is given by $\frac{M}{(R^2 + p^2L^2)^{\frac{1}{2}}}$, and when p is large R may be neglected in comparison with pL.

If $L = 3{,}000$, and frequency 2,000,000,
$p = 12 \times 10^6$ approximately,
$pL = 36 . 10^9$.

Therefore, in order that R^2 may be comparable with p^2L^2, R should be 10 ohms or more.

In the experiments considered, a short carbon rod of 10 ohms introduced into the circuit did not alter the effect on the needle, showing that pL must have been considerably greater in the experiment than in the calculation above. On adding a solenoid of sixty turns in the secondary the fall of deflection was scarcely appreciable, showing that the quantity circulating in the secondary depended on the inductance and not on the resistance of the conductors within wide limits.

IV. EXPERIMENTS ON THE DUMB-BELL OSCILLATOR OF HERTZ.

In the experiments previously considered an ordinary short pianoforte-wire 0·032in. in diameter acted very well as a detector, but when we come to rates of oscillation of over 100,000,000 per second a more delicate detector is required.

Some very fine steel wire was taken, glass-hard, and cut up into lengths of 1cm. Twenty-four of these little needles were then built up into one, each being first dipped in paraffin to prevent eddy-currents passing from one wire to the other. This little collection of needles formed a compound magnet, and offered considerable surface to the action of rapidly-varying magnetizing forces. The detector was fixed in the end of a thin glass tube for convenience of handling.

This detector only retained about one-third of its magnetism, on account of the demagnetizing influence of its ends. When magnetized and placed in a solenoid of two or three turns it supplied an extremely sensitive means of detecting and measuring oscillatory currents of high frequency. It was far too sensitive to use in the ordinary leyden-jar experiments, for with one turn of wire round the tube it was completely demagnetized by a discharge.

For frequencies of 100,000,000 and upwards, however, where the quantities of electricity set in motion are in general small, it gave very satisfactory results.

Plate XLIX., Fig. 11.

B and C were two plates of metal about 20cm. square, arranged as in Hertz's experiment. A small solenoid of two turns (which did not use more than 2cm. of wire) was placed in series with discharge circuit at D. When an induction coil causes a discharge at A, oscillations are set up, which have a frequency in this case of over 100,000,000 per second.

When two turns were wound round the detector, the deflection fell from 300 to 250 in one direction and 300 to 274 in the other, showing that the decay of amplitude of the oscillations is about equal to that of the ordinary leyden-jar discharge.

It is unfortunate that I did not particularly distinguish between the "active" spark and the "ordinary" spark. Hertz had observed that the active spark was the only one that set up oscillations in neighbouring conductors; and from the very rapid decay of amplitude in this case it is almost certain that it was not the "active" spark that occurred.

This is confirmed by the fact that the effects on the needle differed very little whether the spark was obtained by the use of the Voss machine or from a Rumkhorff coil, while Hertz expressly states that oscillations in a neighbouring conductor are not excited unless a large Rumkhorff coil is used, and cannot be excited at all by the use of a Voss machine.

The effect of currents in a resonating circuit was next investigated.

Plate XLIX., Fig. 12.

This experiment was arranged after the same method as Hertz's experiments. C and C′ were two conductors of small capacity attached to ends of circuit in order to give discharging circuit a sensible capacity; *a b c d* was the resonating circuit, *m* spark-gap in resonator.

When discharge passed across *B* oscillations were set up in the resonating circuit. The detector was placed in the side *c a* of the resonator, and when there were three turns of wire round detector deflection fell from 300 to 253.

It was not at all necessary that a spark should occur at *m* to get an effect on needle, the effect being still considerable when the knobs at *m* were 1ft. or more apart.

If one side of the rectangle was removed an effect was still observed, but not of such magnitude as when the circuit was in unison with the primary.

In rapidly-oscillating fields, therefore, iron is magnetized in open circuit. The rapid surgings in a conductor are quite sufficient to demagnetize iron, and no complete circuit is required. The use of a sensitive detector as a means of investigating waves along wires will be discussed later.

It has been shown that iron still exhibits magnetic properties in fields of over 100,000,000 oscillations per second. A needle may be magnetized or demagnetized in open circuit by the oscillations set up in the wire.

More detailed experiments on the absorption of energy by iron cylinders and resistances of iron wires in rapidly-oscillating fields will now be entered upon.

V. ABSORPTION OF ENERGY BY CONDUCTORS.

This subject has been treated mathematically and experimentally by J. J. Thomson ("Recent Researches," pages 321–326). He has there shown, by observing the effects of a discharge on a specially-prepared vacuum-tube, that an iron cylinder absorbs considerably more energy than a copper one. The experimental method pursued here is entirely different from Professor J. J. Thomson's, but the final results obtained are the same. The results are also quantitative, while Thomson's method only admitted of qualitative results.

Plate XLIX., Fig. 13.

An ordinary leyden-jar was discharged through a spark-gap A. In the discharge circuit was a solenoid C, consisting of about thirty turns, and 14cm. long, and about 1cm. in radius. A small coil B of three turns was used as a "detector" solenoid.

The magnetized detector was placed on the small solenoid, and about twenty discharges passed in one direction. The deflection due to the needle was then steady, and remained unaltered however many more discharges were passed.

Suppose, for example, the deflection fell from 200 to 100. The needle was again magnetized in a solenoid close at hand, and another twenty discharges passed in the opposite direction. If in this case the first oscillation tended to magnetize the iron and the second oscillation to demagnetize, the final deflection would be higher, as the amplitude of the second half-oscillation is less than that of the first. Suppose the deflection fell from 200 to 150, the needle was again magnetized and replaced.

A cylinder of iron was then placed in the large solenoid, and twenty discharges passed—(1) In one direction, (2) in opposite direction. In (1) the deflection fell from 200 to 103; in (2) the deflection fell from 200 to 162.

We see, then, that the effect of the iron cylinder in the solenoid is to reduce the amplitude of the second half-oscillation considerably, for when the iron is removed and discharges passed the deflection falls from 200 to 150, and when the iron is in the solenoid from 200 to 162.

We must now consider to what this effect is due. If the iron increased the inductance of the circuit the effect would be to increase the amplitude of the second half-oscillation rather than decrease it. The iron cannot sensibly alter the inductance of the circuit, for we observe that the effect of the first half-oscillation is diminished very slightly—in this particular case from 200 to 100 to 200 to 103.

The result must therefore be due to an absorption of energy by the iron core, and a consequent increase of actual resistance in the circuit. The absorption of energy represents an addition of real resistance to the circuit, and increases the rate of dissipation of energy in the circuit.

The energy absorbed by the conductor may then be readily compared with the energy absorbed when a resistance of very small inductance is placed in the circuit—*e.g.*, a carbon pencil, or a tube containing an electrolyte.

The final deflection when the cylinder was in the solenoid was carefully observed. The cylinder was removed, and a short length of carbon rod of high resistance introduced into the circuit until the added resistance caused the final deflection to be the same as when the metal cylinder was in the solenoid.

Since the damping is identical in the two cases, the added resistance must absorb the same amount of energy as the metal core. The absorption of energy in the metal core therefore increases the impedance of the circuit, and this increase of impedance may be expressed in ohms.

The resistance of the carbon rod or electrolyte was determined for steady currents, and, since the conductivity is small, it will be found, by substitution in the equations given by Lord Rayleigh, that its resistance is practically the same for steady currents as for a frequency of 2,000,000 per second, which is very approximately the frequency of the discharge.

Proceeding in this way, the absorption of energy by various conductors was compared.

(1.) A test-tube was taken and filled with finely laminated soft-iron wires 0·008in. in diameter. In order to insure thoroughly good insulation from eddy-currents the test-tube was filled up with petroleum. The absorption of energy in this case increased the impedance of the circuit 10·25 ohms.

(2.) A test-tube full of steel filings was next placed in the solenoid. Increase of impedance, 9 ohms.

(3.) A thin soft-iron cylinder, 1·9cm. in diameter, 14cm. long. Increase of impedance, 3·9 ohms.

(4.) Solid iron rod. Increase of impedance, 3·5 ohms.

(5.) Copper cylinder, platinum cylinder, a test-tube filled with $CuSO_4$ solution, gave no appreciable absorption of energy.

(6.) A carbon rod, however, absorbed a large amount of energy. Increase of impedance of circuit, 3·3 ohms.

TABLE of Absorption of Energy by Various Conductors. (The absorption of energy is proportional to the increase of impedance of the circuit.)

Substance.	Increase of Impedance.
Laminated soft iron	10·25 ohms.
Solid soft iron	3·5 "
Carbon cylinder	3·3 "
Copper cylinder	Not appreciable.
Platinum cylinder	"
Steel filings	9·0 ohms.

Professor J. J. Thomson ("Recent Researches," pp. 321, 322) shows that the increase of impedance of the primary circuit due to absorption of energy by an iron cylinder of length l and radius a

$$= 4\pi^2 l N^2 \left(\frac{p\mu\sigma}{2\pi}\right)^{\frac{1}{2}} a,$$

where $p = 2\pi n$; n being the number of oscillations per second;

N = number of turns per centimetre of solenoid;

μ = permeability of iron;

σ = specific resistance of iron.

Now, we have shown that a soft-iron cylinder increases the impedance of the circuit by 3·9 ohms.

From this equation we can deduce a rough approximation of the value of μ for iron in fields of high frequency.

The number of oscillations per second was 2,000,000, calculated from data of discharge circuit.

σ is approximate for soft iron, 10^4;

$l = 14$cm.;

$a = 0·95$cm.;

$N = 2$, nearly.

$$\therefore\ 3·9 \times 10^9 = 4\pi^2 \times 14 \,.\, (2)^2 \left(\frac{2\pi \,.\, 2 \,.\, 10^6 \,.\, 10^4\mu}{2\pi}\right)^{\frac{1}{2}} 0·95.$$

An approximate solution of this is $\mu = 172$, which shows that iron has considerable permeability even under the influence of these very transient fields.

It is interesting to observe that it is not necessarily the best conductors that absorb the most energy in these fields: in fact, the very reverse is the case. A copper cylinder does not absorb more than one-fortieth of the energy that an iron cylinder of the same dimensions does, or one-thirtieth of the energy of a carbon rod of the same dimensions. It could always be told whether any considerable amount of energy was being absorbed in the solenoid by the peculiar deadened sound of the spark. A copper cylinder did not deaden the sound like an iron or carbon cylinder. The same sound was caused by adding a carbon rod in series with the circuit, so as to increase the resistance of the circuit.

VI. RESISTANCES OF IRON WIRES FOR HIGH-FREQUENCY DISCHARGES.

Since iron has been shown to retain its magnetic properties in fields which are reversed a hundred million times per second, it was expected that the resistance of iron wires would be much greater for frequencies of several million per second than for steady fields, on account of the concentration of the current on the surface-skin of the conductor.

The resistances of conductors for these very rapid alternations have not yet been able to be determined, and so any method of attacking the difficulty is of interest. The method of experiment was practically the same as that used to determine the absorption of energy in conductors.

Plate XLIX., Fig. 14.

About 4 metres of iron wire were taken, and arranged in a rectangular discharge circuit. The other wire connections were copper conductors of the same diameter as the iron. The fall of deflection in the "detector" was observed for a series of discharges first in one direction and then in the other. The iron wire was then removed, and a copper wire of the same radius and length substituted. This insured that the self-inductance of the circuit was practically unaltered. A short carbon resistance was then added in the circuit until the fall of deflection with the copper wire and the carbon resistance was exactly the same as the fall of deflection in the case of the iron wire. Where this is the case, the resistance of the iron is equal to resistance of copper wire of equal length together with the carbon resistance.

Example of the Method of Determination.

When iron wire is in circuit, deflection falls—(1) From 200 to 103 for one direction; (2) from 200 to 176½ in opposite direction.

When the iron wire was removed, and a copper one substituted, the fall of deflection was—(1) From 200 to 101 for one direction; (2) from 200 to 162 for opposite direction.

On the addition of a carbon resistance of 8·5 ohms to the discharge circuit, the fall of the deflection was—(1) From 200 to 103; (2) from 200 to 176½.

Since the fall of deflection is the same in the two cases, resistance of iron wire = 8·5 ohms + resistance of the copper wire for that particular period. Now, from Lord Rayleigh's equations, the resistance of copper wire in rapidly-alternating fields is given by $R' = \sqrt{\tfrac{1}{2} p l R}$, where l = length of wire, and R is resistance of wire for steady currents. From knowledge of the period this may readily be calculated. The resistance of the iron wire is therefore known.

In order to determine the period very accurately, a plate condenser was used with ebonite as the dielectric. The S.I.C. of ebonite had been determined previously and found to be 2·2. The capacity of the condenser was found from calculation of the size of the plates to be 460 electrostatic units.

From knowledge of the data of the discharge circuit the self-inductance can be calculated. (See Lodge's "Experiments on Discharge of Leyden-jars," Proc. Roy. Soc., June 4, 1891, p. 33.)

$$\begin{aligned} \text{The self-inductance } L &= 4278\,; \\ \text{frequency } n &= 2\pi\sqrt{LC} \\ &= 3{\cdot}5 \times 10^6\,; \\ \text{and } p = 2\pi n &= 2{\cdot}1 \times 10^7. \end{aligned}$$

The effect of the increase of diameter of wires on the self-inductance of the circuits is small, so that in all cases the number of oscillations per second will be taken as 3,500,000. When the resistances of iron wires of different sections were being determined a copper wire of as near as possible the diameter of the iron wire under consideration was placed in the circuit. In the case of an iron wire 0·22in. in diameter, a lead pipe took the place of the copper conductor.

After the calculated resistance of the copper wires for a frequency of 3,500,000 had been added to the carbon resistance placed in the circuit, the following is the table of resistances observed:—

Wire.	Diameter.	Resistance for Steady Currents.	Resistance for a Frequency of 3,500,000.
	In.	Ohms.	Ohms.
(1.) Soft iron	0·011	8·5	14
(2.) Soft iron	0·039	1·17	9·2
(3.) Steel pianoforte-wire ..	0·032	1·59	10·7
(4.) Nickel wire	0·043	0·59	7·2
(5.) Soft-iron wire	0·145	0·07	4·9
(6.) Soft-iron wire	0·222	0·032	4

It will be observed that for the soft-iron wire 0·222in. in diameter the resistance of the wire is 125 times its resistance for steady currents.

The wire 0·145in. in diameter is seventy times its ordinary resistance, and wire 0·039in. about eight times.

The general result of this investigation supports the theory of increase of resistance of conductors as the rapidity of the oscillations is increased.

The experiments here recorded receive additional confirmation from later investigations on the circular magnetization of iron.

It will be observed that the wire 0·011in. in diameter does not double its ordinary resistance for a frequency of 3,500,000, and the resistances increase more rapidly for increase of diameter than ordinary theory would lead us to expect.

Lord Rayleigh has shown that the resistance of a wire of permeability μ for rapidly-alternating fields is $\sqrt{\frac{1}{2}\mu p l R}$, where R = resistance for steady currents.

Now, for wire of diameter 0·222in.,

$$\sqrt{\tfrac{1}{2}\mu p l R} = 4\,;$$

and substituting $p = 2{\cdot}1 \times 10^7$,
$l = 377$,
$R = 0{\cdot}032$ ohm,

we get an equation for μ, and it will be found that in this case $\mu = 121$; and, if we thus determine μ for the different soft-iron wires, we get the following table:—

Diameter.	Calculated Permeability.
0·011in.	5·8
0·039in.	18
0·145in.	87
0·222in.	121

It will be observed that the apparent permeability of the wire increases proportionately to the radius. Where the radius of wire is increased twenty times, permeability is increased twenty times, and so on.

I am not aware that anything definite on this subject has been hitherto done; but the following approximate calculation possibly gives the true explanation:—

Consider a condenser charged with a quantity Q_0 of electricity.

The maximum current of discharge $J = pQ_0$, assuming no decrease in amplitude.

Now, if this current be confined to a surface-skin of the conductor, the magnetic force, at a distance r from the centre, is given by

$$H = \frac{2J}{r}\,.$$

Now, this value of H at any point only depends on the current flowing external to that point; and, since the current is mainly confined to the surface, we may take $r =$ radius of wire.

$H = \frac{2pQ_0}{r} = \frac{2}{r}pCV_0$, where V_0 is potential between knobs, and C is capacity of condenser.

As the spark-gap was $\frac{1}{10}$in. in length, the difference of potential was as near as possible 10,000 volts. Substituting these values, it will be found that

$$H = \frac{18\cdot 8}{r} \text{ nearly.}$$

For the first wire $r = 0\cdot 011\text{in.} = 0\cdot 027\text{cm.}$

$$\therefore H = \frac{18\cdot 8}{0\cdot 013} = 1{,}400 \text{ approximately;}$$

and, taking $B = 12{,}000$, we get a value of

$$\mu = \frac{B}{H} = 9 \text{ approximately.}$$

The observed value is about 6; but the discrepancy between the two results is to be expected, and is due to the fact that the resistance of the iron is measured after a succession of discharges in the same direction, when, on account of the greater amplitude of the first half-oscillation, the inner part of the wire is practically saturated, and does not offer any considerable permeability when once the current has penetrated through the external skin, magnetized in the opposite direction by the second half-oscillation. The equations $H = \frac{2J}{r}$ and $\mu = \frac{B}{H} = \frac{Br}{2J}$ show that we should expect the permeability of the iron to vary as the radius of the wire, within, of course, the maximum limit of permeability of iron—*i.e.*, about 3,000. The table given previously shows how closely the law is fulfilled in practice.

Now, $J = pQ_0 = \frac{1}{\sqrt{LC}} CV_0$, and V_0 varies as the spark-length d.

$$\therefore J \propto \frac{\sqrt{C}}{\sqrt{L}} \cdot d,$$

and $\mu = \frac{Br}{2J}$, and when the iron is saturated B may be taken as constant.

$$\therefore \mu \propto \frac{r\sqrt{L}}{d\sqrt{C}}.$$

Therefore increase of radius increases the permeability of iron in these fields, and the shorter the spark-gap the higher the permeability, and therefore the resistance.

The resistance R′ for high frequencies $= \sqrt{\tfrac{1}{2}\mu_0 p l \mathrm{R}}$.

$$\therefore \ \mathrm{R}' \propto \sqrt{\tfrac{1}{2}\,\frac{r\sqrt{\mathrm{L}}}{d\sqrt{\mathrm{C}}}\cdot\frac{l}{\sqrt{\mathrm{CL}}}\cdot\frac{l}{r^2}}.$$

$$\propto \frac{1}{\sqrt{rcd}}, \text{ where } l \text{ is constant.}$$

The resistance of iron wires in these fields varies inversely as the root of the radius, inversely as the root of the capacity, and inversely as the root of the spark-length, and is independent of the inductance of the circuit.

The increase of resistance of iron wires for rapidly-alternating currents has been ascribed to the concentration of the current on the surface of the conductor. There is also, of course, loss of energy by hysteresis on account of the magnetization and demagnetization of the iron wire. Although much more energy is absorbed in steel than in soft iron, due to hysteresis, the steel wire did not show any greater increase of resistance than the soft-iron wire. It seems, therefore, that the effect of hysteresis may be neglected as a factor in determining the increase of resistance of wires.

It is possible that the absorption of energy due to hysteresis may be much greater for a frequency of several millions than for frequencies of 1,000; but it is a very difficult matter to separate the effects of induced currents from those of hysteresis in causing absorption of energy in an iron cylinder.

VII. ON THE DIVISION OF RAPIDLY-ALTERNATING CURRENTS IN MULTIPLE CIRCUITS, AND THE EFFECT OF METAL CORES ON THE DISTRIBUTION OF THE CURRENT.

Plate XLIX., Fig. 15.

Consider the distribution of an alternating current between two conductors A C B, A D B, in parallel.

Let R and L be resistance and self-inductance respectively in branch A C B.

Let S and N be resistance and self-inductance respectively in branch A D B.

If y be current in branch A C B, and $x-y$ be current in branch A D B, then it is shown ("Recent Researches," p. 513) that for rapid alternations the distribution is such that

$$y = \left\{\frac{\mathrm{S}^2+\mathrm{N}^2\mathrm{P}^2}{(\mathrm{L}+\mathrm{N})^2+(\mathrm{R}+\mathrm{S})^2}\right\}^{\frac{1}{2}} \cos.\,(pt+\epsilon),$$

$$x-y = \left\{\frac{\mathrm{R}^2+\mathrm{L}^2\mathrm{P}^2}{(\mathrm{L}+\mathrm{N})^2+(\mathrm{R}+\mathrm{S})^2}\right\}^{\frac{1}{2}} \cos.\,(pt+\epsilon'),$$

where $\quad \tan.\,\epsilon = \dfrac{p\,(\mathrm{RN}-\mathrm{SL})}{\mathrm{S}\,(\mathrm{R}+\mathrm{S})+\mathrm{N}\,(\mathrm{L}+\mathrm{N})\,p^2},$

and $\quad \tan.\,\epsilon' = \dfrac{-p\,(\mathrm{RN}-\mathrm{SL})}{\mathrm{R}\,(\mathrm{R}+\mathrm{S})+(\mathrm{L}+\mathrm{N})\,\mathrm{L}p^2}.$

The maximum currents flowing in the two branches are proportional to the quantities under the roots, and it will be observed that the distribution of current for high frequencies depends more on the self-inductance than on the resistance of the circuit.

The two circuits were wound exactly equal to one another. Each consisted of a solenoid of 34 turns, 22cm. long, 2·2cm. in diameter. The wire was indiarubber-covered copper wire 0·039in. in diameter.

When a metal core is introduced into the solenoid and a discharge passed there are vigorous induced currents in the cylinder. When it is considered that a current of sometimes 100 amperes is reversed 10,000,000 times per second, the induced currents must be large. These induced currents, on account of the very short time which they last, are confined to a thin skin of the cylinder. But these induced currents tend to diminish the effective inductance of the circuit. The amount of energy absorbed in the cylinder depends on the difference of phase between the direct and induced currents. The impedance of the circuit is given by $\sqrt{R^2+p^2L^2}$, and it is of interest to know whether this is increased or decreased by the introduction of a metal core.

(1.) A copper cylinder 1cm. in radius was introduced into one solenoid. By the use of an ordinary detector it was found that more current flowed in the branch in which the copper cylinder was placed than in the other branch. The amount of current in one branch was 8 per cent. more than in the other. Now, from the expressions given for the distribution of current in each branch, it will be seen that the denominators of the expressions are the same, and the numerators represent the impedances of the circuits. The value of $\sqrt{R^2+p^2L^2}$ is decreased by about 8 per cent. by the introduction of the copper cylinder, or the effect of a copper core is to *diminish the impedance* of the circuit.

(2.) When a lead cylinder was introduced in place of the copper no effect of unequal distribution could be with certainty detected.

(3.) *Magnetic Cylinders.*—(*a.*) When a solid soft-iron cylinder was introduced into the solenoid the current in that branch was diminished by about 3½ per cent. (*b.*) Laminated soft-iron wires placed in test-tube and thoroughly insulated from one another decreased the current in its branch by more than 12 per cent. (*c.*) Steel filings in a test-tube also decreased the current in its branch.

The effect of iron, whether solid or finely divided, is therefore to increase the impedance of the circuit.

This is the general result obtained for a frequency of about

3,000,000 per second, but whether the increase of impedance is due chiefly to an increase of R or of L, or both, cannot be definitely settled; but from experiments of the great absorption of energy of iron cylinders it is most probable that the increase of the impedance is due to an increase in R, and not to an increase in L.

A far more delicate arrangement for detecting differences of resistance and inductance in circuits was used in further experiments. A differentially-wound solenoid was used with one coil in one branch and a similar coil in the other, such that when the currents in each branch were alike in amount and phase there was no effect on the "detector" placed in the solenoid. If a metal core was introduced into either solenoid the balance was greatly disturbed, and in this way the results of previous experiments were confirmed. The method offered a very convenient means of determining the resistance of iron wires, and the values obtained were quite in accordance with previous results.

VIII. CIRCULAR MAGNETIZATION OF IRON WIRES.

While experimenting on the resistance of iron wires which passed close to the magnetometer, it was observed that the deflection of the magnetometer varied very considerably with the direction of the discharge, and also with the number of discharges. The reason was at first not clear, but subsequent investigation showed that it was due to the magnetization of a neighbouring part of the wire by the transient current that passed through it. When the wire was quite straight no effect was observed, but if a slight bend was made near the magnetometer the deflection varied according to the direction of the discharge. The effect was very marked both in soft-iron and steel wires, and shows what heavy momentary currents must be circulating in the wires, for a steady current of 10 amperes did not affect the deflection appreciably. The effect of discharges through a short wire magnetized longitudinally was then investigated. The discharge always reduced the magnetization, whether the wire was of soft iron or steel. This apparent demagnetization of the iron was due to the surface-skin being "circularly" magnetized by the longitudinal current through the wire. The heavier the transient current the greater was the fall of magnetization.

The following are examples of a few of the experiments on the fall of deflection when the frequency of discharge was 3,000,000 and the value of the maximum current about 100 amperes:—

(1.) Thin soft-iron wire, 0·01in. in diameter: Completely demagnetized.

(2.) Thin steel wire, 0·01in. in diameter: Completely demagnetized.

(3.) Pianoforte steel-wire, 0·032in. in diameter: Deflection fell from 250 to 116.

(4.) Steel needle, 0·065in. in diameter: Deflection fell from 250 to 184.

(5.) Thick steel needle, 0·102in. in diameter: Fall of deflection from 250 to 216.

(6.) Hollow soft-iron cylinder, ¼mm. thick, diameter 18mm., length 16cm.: Fall of deflection, 250 to 230.

The same condenser and discharging circuit were used for all the specimens tested, and it is of interest to observe the depth of penetration inwards, assuming the residual deflection is given by the mass of iron not circularly magnetized—*i.e.*, not affected by the current in the surface-skin of the conductor.

Wire.	Diameter.	Depth of Penetration of the Discharge.
	In.	In.
Hard-steel wire	0·032	0·0051
Soft-steel wire	0·065	0 00455
Soft-steel wire	0·102	0·00357
Soft-iron cylinder	0·72	0·00044

Experiments of this kind show to what a small depth the current penetrates into the wire. Very large momentary currents are conveyed through a thin surface-skin of the conductor, and the intensity of the current diminishes rapidly inwards.

The loss of deflection due to the "circular magnetization" of a wire by the passage of a longitudinal current is a very convenient method of estimating the quantities of electricity that flow in the branches of multiple circuits.

The currents in this case are all of the same frequency, and, experimentally, it was found that the "depth of penetration" was proportional to the maximum current.

By taking short steel needles magnetized to saturation and placing them in series with circuits in multiple arc, the division of the current among the conductors admits of accurate determination. By varying the diameter of the needles, currents of the same period but widely different amplitudes may be compared.

J. J. Thomson has suggested a specially-prepared vacuum-tube placed in a solenoid as a convenient galvanometer for discharges of this kind. The comparison between the currents in the various branches is made by observations on the brilliancy of the discharge in the bulb. The effect of a longitudinal current on the magnetism of a needle, however, not only gives a qualitative method of comparison, but also very accurate quantitative results.

In the earlier part of this paper it has been shown that a magnetized needle is demagnetized considerably under the influence of an oscillating discharge of a frequency of about 100,000,000, such as is obtained from Hertz's dumb-bell oscillator.

Plate XLIX., Fig. 16.

A and B were two metal plates of small capacity, S the spark-gap. A small steel needle, C D, diameter 0·01in., was placed in the discharge circuit. After the passage of several discharges the deflection of the needle fell from 300 to 250: this corresponds to a depth of penetration of the discharge of about 0·00045in. Sending several discharges in the same direction had the effect of decreasing the deflection till a steady state was arrived at, exactly as in the case of the demagnetization of iron needles in solenoids.

From the magnitude of the effect we have been considering, it is evident that a thin magnetized needle is a very convenient galvanometer for the measurement of the intensity of electric waves at different parts of a circuit vibrating freely.

In order to see if this were the case, the experimental arrangement of Hertz for showing the existence of waves along wires was used.

Plate XLIX., Fig. 17.

The plate B was about 10cm. behind the plate A. A wire was taken from B to C, about 5 metres long.

If the end C were free and insulated, and the small detector placed in series near the end, no effect on the needle was produced. If a metal plate were fixed to the end C, there was immediately a fall of deflection of 50 divisions when the vibrator was set working. This shows that when the end is free the point C is a position of minimum current, and when the plate is added the current is a maximum at C. On leaving the end free, and moving the needle to different distances from C, the fall of deflection gradually increased, and then diminished again.

The experiment was not proceeded with, as the subject of the distribution of waves along wires has been worked out experimentally by several methods. It shows, however, that a magnetized needle is a very convenient galvanometer for oscillating circuits for frequencies up to 500,000,000 per second.

The effects on fine steel wire, whether placed in series or in a solenoid of several turns, may be used as a means of detecting electro-magnetic radiation, and of investigating the waves in free vibrating circuits.

Before starting this research I was uncertain whether iron was magnetic in very rapidly-oscillating fields or not. The only information I could obtain on the subject is given in the opening pages. What experimental evidence there was seemed vague and contradictory. In this research, starting from the magnetization of iron in ordinary leyden-jar discharges, it has been shown that iron is magnetic for frequencies up to 500,000,000 per second. On account of the small quantities of electricity set in motion the experiments were not pursued further, but I have no doubt that by the use of very thin steel wires iron may be shown to be strongly magnetic for the highest frequencies yet obtained. If the molecules of iron can follow the changes of magnetic force, which is reversed 1,000,000,000 times per second, there can be very little magnetic viscosity, and the molecules must move as freely as when under the influence of an alternating current of 100 per second.

Iron has been shown to absorb energy and exhibit high permeability in very rapidly varying fields; the absorption of energy has also been accurately measured. The resistance of iron wires for leyden-jar discharges has been investigated, and an approximate theory advanced to account for the effects observed. In one case the resistance has been shown to be 120 times the resistance for steady currents.

The division of currents in multiple circuits has been investigated in several cases, and it has been shown that iron, whether solid or finely divided, always increases the impedance of a circuit.

The use of magnetized steel needles as "detectors" and "galvanometers" has been explained, and their possible use also for measurement of the intensity of electro-magnetic waves.

Information with regard to the nature of the discharges and the damping of vibrations has been obtained in the course of the experiments.

A more detailed though imperfect note is appended on the "Resistance of Spark-gaps," a subject on which little seems to be at present known.

NOTE ON RESISTANCE OF SPARK-GAPS.

When a leyden-jar is discharged a bright flash of light is the only apparent result of the energy stored up in the dielectric of the jar. The energy of the discharge, however, has been dissipated, due to several distinct causes.

(1.) The spark-gap offered resistance to the discharge, and energy has been dissipated in the air-space according to Joule's law.

(2.) The wires and connections of the discharge circuit have also dissipated part of the energy into heat. It must be remembered in this connection that the resistance of wires for leyden-jar discharges is often much greater than for steady currents.

(3.) Part also has been radiated away into space as electromagnetic waves. The amount of this radiation varies greatly with the type of condenser used. An ordinary leyden-jar is a poor radiator, but Hertz's dumb-bell vibrator is a good radiator and the oscillations are rapidly damped down.

(4.) Part also has been absorbed in the dielectric, due to molecular hysteresis in the glass. The amount of this is not known with certainty, and it most probably varies greatly with the kind of glass used.

For the ordinary leyden-jar most of the energy is wasted in heat in the spark-gap, and the number of complete oscillations that occur depends almost entirely on the length of spark-gap. Indirect evidence of the rapid damping-down of vibrations is afforded by experiments on resonators. If the discharge circuits of two equal condensers be exactly equal and facing one another, a few feet apart, when one jar is discharged oscillations are set up in the neighbouring circuit, and since the periods of the two systems are the same the well-timed impulses due to the vibrator will cause sparking in the resonator.

The distance to which this sparking may be detected depends almost entirely on the length of the spark-gap in the circuit of the vibrator. When the spark-gap is long, although the first oscillation is very vigorous no sparks can be detected in the resonator more than a few feet away. As the spark-gap is shortened the oscillations of the vibrator diminish in amplitude, but are more persistent on account of the lower resistance in the spark-gap, and, as the resonator responds more readily to a succession of small impulses than to one vigorous impulse, sparking may be detected to a much greater distance. For spark-gaps greater than $\frac{1}{10}$in. in length an ordinary discharge is damped down extremely rapidly, and the amplitude of the second swing is generally less than a fifth of the first.

When a discharge occurs in currents of known inductance and capacity the theoretical law of decay is known. The current J at any instant t is given by

$$J = \frac{CV_0}{(LC)^{\frac{1}{2}}} e^{-\frac{R}{2L} \cdot t} \sin. \frac{t}{(LC)^{\frac{1}{2}}}$$

where L = inductance of circuit for rapid oscillation,
R = resistance of leads and spark-gap,
C = capacity of jar,
V_0 = potential of coatings.

The maximum current of the first half-oscillation is given by

$$J_1 = \frac{CV_0}{(LC)^{\frac{1}{2}}} e^{-\frac{R}{2L} \cdot \frac{T}{4}},$$

where T is period of a complete oscillation.

The maximum current of the second half-oscillation is given by

$$J_2 = \frac{CV_0}{(LC)^{\frac{1}{2}}} e^{-\frac{R}{2L} \cdot \frac{3T}{4}}.$$

$$\therefore \log. \frac{J_1}{J_2} = \frac{R}{2L} \cdot \frac{T}{2}. \qquad \text{(A.)}$$

The ratio $\frac{J_1}{J_2}$ can be obtained by the method of experiment previously explained; and, since T and L are known from the data of the condenser and the discharge circuit, R is known. Now, R is made up of the resistance of the leads as well as the spark-gap. The resistance of the leads can be deduced from Rayleigh's formula, and therefore the resistance of the spark-gap between the first and second half-oscillations is known.

An experimental method of calculation was also used as a means of checking the results obtained from above equation. After the ratio $\frac{J_1}{J_2}$ had been determined by varying the number of turns in a solenoid, a known carbon resistance, r, was introduced into the circuit, and the ratio, $\frac{J_3}{J_4}$, of the first two half-oscillations determined as before.

$$\therefore \log. \frac{J_3}{J_4} = \frac{(R + r)}{2L} \cdot \frac{T}{2}. \qquad \text{(B.)}$$

Dividing equation (B) by (A), we get—

$$\frac{R + r}{R} = \frac{\log. \frac{J_3}{J_4}}{\log. \frac{J_1}{J_2}}.$$

Therefore R is known at once.

Proceeding in this way, the resistances of spark-gaps when the self-inductance and spark-length were constant and the capacity varied were determined. The spark-gap was $\frac{1}{10}$in. in length, and between knobs 1cm. in radius.

Condenser.	Capacity.	Ratio of Amplitude of First to Second Half-oscillation.	Resistance of Spark-gap in Ohms.
			Ohms.
Two leyden-jars in series ..	500	2·55	50·5
Plate condenser	576	2·42	49·3
One leyden-jar	1,000	1·85	24·5
Two leyden-jars in parallel ..	2,000	1·84	17·2
Four leyden-jars in parallel ..	4,000	2·01	13·6
Six jars in parallel	6,000	2·1	10·5

A Voss machine was used to charge up the jars. It will be seen that the resistance of the spark-gap diminishes rapidly as the capacity of the condenser is increased—*i.e.*, as the quantity of electricity that passes through the spark-gap is increased.

The effect of keeping the capacity and inductance constant and varying the spark-length was then proceeded with.

Length of Spark-gap.	Ratio of Amplitudes of First Two Half-oscillations.	Resistance of Spark-gap in Ohms.
In.		Ohms.
0·014	1·31	14·8
0·028	1·44	19·8
0·089	2·31	47·8
0·1	2·42	51·3
0·142	2·91	60
0·231	4·4	81

These observations show that the spark-gap increases in resistance rapidly as the length of spark is increased. Short spark-gaps have low resistances, and long spark-gaps high resistances.

In all these experiments a Voss machine was used to charge up the jars. If the Voss is replaced by a Rumkhorff coil, under certain conditions it is probable that the resistance is much lower. If a Hertz dumb-bell vibrator is excited by a Voss no action in a resonator can be detected. When a Rumkhorff coil is used oscillations are set up in neighbouring circuits, but only when a certain kind of spark is given by the coil. This spark was called by Hertz the "active" spark, and it is probable that the resistance of the spark-gap is much less with the active spark than with the ordinary discharge. Usually with a spark-gap of about ⅔cm. the vibrations are damped down very rapidly, and the second half-oscillation has not half the amplitude of the first.

In the course of one experiment I tried whether there was any difference in the resistance of the gap when a Voss was used or a coil. The results were,—

(1.) The condenser was charged up to a slightly greater difference of potential by the Rumkhorff than by the Voss for the same length of spark-gap.

(2.) The resistance of the spark-gap for the Rumkhorff coil discharge was slightly less than in the case of the Voss.

These are the results of a few preliminary experiments into this little-known subject. I have reserved a more complete investigation for a future occasion.

ART. LX.—*The Last Glacial Epoch: explained by Major-General Drayson's Discovery of the Second Rotation of the Earth.*

By Major-General SCHAW, C.B., R.E.

[*Read before the Wellington Philosophical Society, 13th June, 1894.*]

Plate XLV.

As you have re-elected me as your President for the present year, the duty once more devolves upon me to open the session by an inaugural address, and I have chosen as my subject one which I hope may give rise to some interesting and instructive discussion—namely, that slow movement of the north pole of our earth which has long been known in an imperfect manner, but which has now been reduced to mathematical exactness by Major-General Drayson, and discovered by him to be caused by a second rotation with a very long period. The bearing of this discovery upon the date and duration of the last glacial epoch, and the explanation which it affords of that peculiar epoch of the earth's history which immediately preceded man's appearance, are extremely interesting, and I propose to bring the whole matter briefly in review before you this evening.

In speaking of an ice age or a glacial epoch, I do not refer to anything like a cataclysm, but simply to an extension southwards in the Northern Hemisphere and northwards in the Southern Hemisphere of climatic conditions such as now exist within and near the arctic and antarctic circles. And I assume that this extension of refrigeration was not sudden in its beginning or its ending, but was gradual and slow, and that the effects of such refrigeration were different in different