June 4, 1891.

Sir WILLIAM THOMSON, D.C.L., LL.D., President, in the Chair.

The Presents received were laid on the table, and thanks ordered for them.

The following Papers were read:—

I. "Experiments on the Discharge of Leyden Jars." By OLIVER J. LODGE, F.R.S. Received May 2, 1891.

EXPERIMENTS ON THE DISCHARGE OF LEYDEN JARS.

The following experiments among others were made in the course of 1888, beginning in February of that year. A brief account of the early experiments, with some of the deductions from them, was given in a couple of lectures to the Society of Arts in March, 1888, on Lightning Conductors; and in the 'Electrician,' vols. 21, 22, 23, under the same title, a number of others were published at length, viz., the series of experiments relating to "the alternative path." But the rest of the experiments has never been published in any detail; though, as they led to some interesting observations concerning electromagnetic waves, and incidentally measured the velocity of transmission of a pulse along an isolated wire, they ought to have been written out for publication long ago.

I now venture to communicate them to the Royal Society, beginning with such brief account of the earliest experiments as may suffice to render the steps intelligible.

Description of Jars Used.

1. The pattern of jar ordinarily used was an open cylinder without lid or neck, with the charging rod firmly supported from the interior and quite free from the glass above the tinfoil.

They were of two principal sizes, which I call for short "gallon" and "pint."

Each gallon jar was 40 cm. high and 13 cm. diameter, coated to within 10·5 cm. of the top; and the capacity of the pair chiefly used was 0·0062 microfarad each. Two in series had a capacity of 28 K metres. Each pint jar was 16·5 cm. high and 8·2 cm. diameter, and was coated to within 5 cm. of the top. The capacity of the one chiefly used was 0·0016 microfarad. Two pint jars in series had a capacity of 6·6 K metres.

In addition to these ordinary jars, a couple of large condensers were made, each consisting of 16 pairs of 11-inch square tinfoil sheets, separated by double thicknesses of window glass, each pane about $\frac{1}{10}$ inch thick, and with a good margin; tinfoil strip connectors protruding on alternate sides, and copper wire prolongations, with all joints soldered, terminating in a pair of knobbed rods projecting upwards through stout glass tubes more than a foot apart; the whole thoroughly soaked and embedded in a mass of paraffin, poured molten into a strong teak outer case 22 × 20 × 13 inches, the whole when finished weighing about 3 cwt.

The capacity of one of these condensers was 0·028, of the other 0·02, microfarad. Single glass thickness would have given much greater capacity, but preliminary experiments showed that single thicknesses of glass were punctured by very modest sparks.

It is important in these experiments to have joints better made than is usual for high-tension electricity. Fizzing or sparkling inside jars is abominable.

ACCOUNT OF THE LONG CONDUCTORS USED IN THE EARLY EXPERIMENTS.

2. Round the Lecture Theatre,* supported on four vertical posts a good way from every wall, were stretched and supported, either by silk thread or silk ribbon according to the strength demanded, four or five wires, two of them of copper, one thick (No. 1 B.W.G.) and the other thin (No. 19); two of them of iron, one thick (No. 1) and the other thin (No. 18). They are called respectively "long thick copper," "long thick iron," "long thin copper," "long thin iron." Sometimes a "thinnest iron" of No. 27 B.W.G. was used too. The thick wires formed a rude rectangle 840 × 515 cm.; being joined mechanically not far from their ends by a foot or so of silk ribbon, and sufficient free ends being left to connect directly with jars or machine; connexion being usually made by wrapping tinfoil tightly round the joined conductors. The thinner wires formed rather larger rectangles.

Particulars of these conductors here follow :—

	Length.	Diameter.	Ordinary resistance.	Approximate effective inductance.	Approximate capacity.
No. 1 copper	27·1 metres	0·74 cm.	0 025 ohm	390 metres	5 metres
No. 1 iron ..	27·1 ,,	0·71 ,,	0·088 ,,	390 ,,	5 ,,
No. 19 copper	30·3 ,,	0·085 ,,	2·72 ,,	570 ,,	3½ ,,
No. 18 iron..	30·3 ,,	0·12 ,,	3·55 ,,	550 ,,	3½ ,,
No 27 iron..	30·3 ,,	0·035 ,,	33·3 ,,	630 ,	3 ,,

---

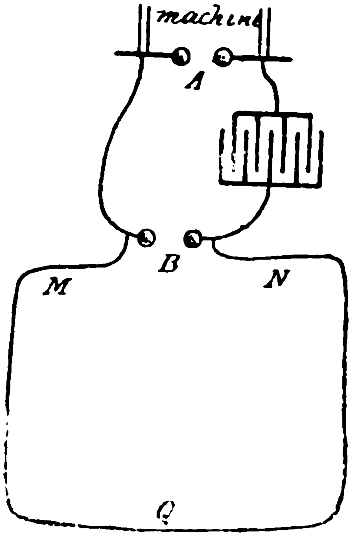
* University College, Liverpool.

The copper is commercial quality and evidently of miserable conductivity. I afterwards got some real copper from Messrs. Thos. Bolton and Sons, and with it the phenomena are still better marked.

EARLY EXPERIMENTS.

3. The large glass condenser (0·028 mfd.) was charged through one or other of the long wires, and a choice was offered the discharge, so that it might go either round the wire or leap an air-gap, as it chose; as shown in fig. 1.

FIG. 1.



A are the ordinary terminal knobs of the Voss or Wimshurst machine where the spark occurs; B is the discharge interval acting as a shunt to the wire or other resistance. MQN represents diagrammetrically one of the wires round the room. The spark-length B was adjusted so that it was an off chance whether the discharge chose it or the wire. It was noticed that when the discharge chose B the A spark was strong, but when the discharge chose the wire the A spark was weak. The difference appeared to be only in the noise or suddenness of the spark, for when a Riess's electro-thermometer was inserted in the circuit it indicated about the same in either case.

A capillary tube was filled with very dilute acid so that its resistance was about ¼ megohm, and was connected across the B knobs instead of the long wire. When this acid tube was thus made the alternative path, and the B knobs placed so far apart that the discharge was obliged to choose it, the A spark was very weak, being reduced to a quiet spit, which could be analysed by a slowly rotating mirror into several detached sparks.

After a number of readings of spark-length, which have been elsewhere published (and which showed among other things that it made very little difference whether the alternative path were copper or iron), a common Leyden jar was substituted for the condenser, and similar results were obtained with it.

But it was now noticed, in addition, that the jar frequently overflowed by sparking over its lip; and that when this happened a spark still occurred at B though not at A.

A special overflow or short-circuiting path was then provided, equivalent to a pair of discharging tongs; calling this air-gap C, it was found that, according to the adjustment of the width of spark-gaps, flashes at B and C could be got without A; or at A and B without C; or at C only. (This was the beginning of experiments on overflow.)

Putting acid resistance into the circuit at M or at N weakens but does not stop the B sparks; and it has the same effect at M as at N. But inserting resistance at Q does not weaken the B spark perceptibly; neither does cutting the wire there; only of course, in order to permit the charging of the jar in this case, the B gap has to be bridged by some imperfect conductor; this shunt high resistance, which may be a piece of dry wood or anything just sufficient to convey the *charging* current, having no appreciable effect upon the B spark.

But it was noticed that when the wire was cut at Q a singularly long spark or strong brush discharge attempted to jump the space there whenever the machine spark occurred. (This was the beginning of experiments on "recoil-kick.")

It was also found that connecting the machine side of the jar to earth (the long wire, not interrupted anywhere, being insulated) increased the strength of the B sparks very much, and made them easier to get. Evidently the wire was acting as one coat of a condenser, the wall being the other coat. Even when the jar was discarded, no connexion being made in its place, and the wire alone used, sparks occurred at B perfectly well whenever the machine gave a spark at A. (This led to experiments on "the surging circuit.")

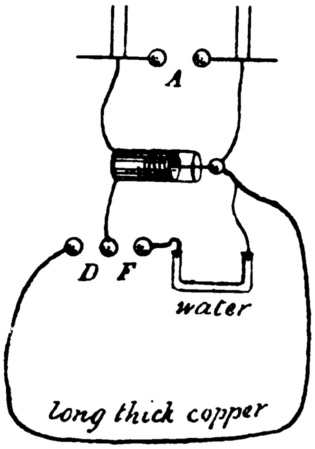
EXPERIMENTS ON OVERFLOW (February, 1888).

Small Jar.

4. Tried the arrangement shown in fig. 2, the jar being pint size, as described above, of plain cylindrical shape, open at top, with its lip projecting 2 inches above the tinfoil so that the overflow distance was 4 inches. The long wire was the 30 yards of No. 1 copper. In addition to the machine spark-gap A, a couple of other intervals labelled D and F were also provided; the spark-gap D being led up to

through the long thick wire, the spark-gap F through the capillary water tube of high resistance already mentioned. The A knobs were each 2·34 cm. diameter. The size of the others does not seem to be recorded.

Fig. 2.



Separating the machine knobs too far for a spark there, sparks could be got either at C or at F or over the lip of the jar, or in two or three places at once. The lengths were D = 0·72 inch, F = 0·68 inch. Bringing the A knobs nearer together, a distance of 0·57 inch, it went there too. The A spark is the noisiest, then D, and lastly F; F is in fact quite weak. When it sparks at D it mostly goes at F too, and likewise overflows the lip of the jar, but not always.

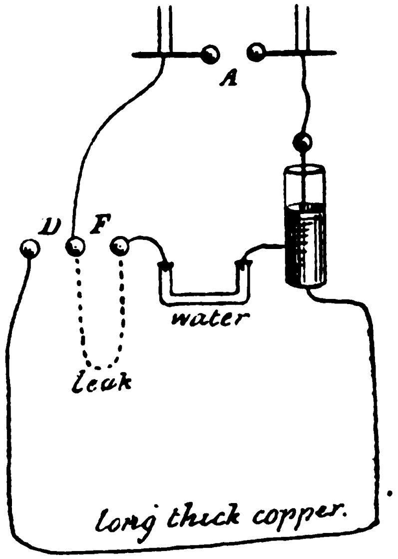
Shorten all the air-gaps so as to avoid overflow, and they spark simultaneously at the following distances :—

A.	D.	F.
0·435	0·565	0·575

Modified the plan of connexions to that shown in fig. 3 ; the second water resistance or "leak" being now introduced merely in order to give the jar the possibility of charging.

Whenever an A spark occurs, a considerable range is permissible with the others. As to F, it does not matter how short that is made ; it is affected by the others, but has no effect on them. The overflow of jar specially accompanies a spark at D. Frequently sparks occur in all four places at once ; and at times the overflows of jars are violent and numerous, so that, when A and D are both pretty long, flashes fly from cork and wood and almost anything that happens to be in contact with the jar. (The jar stood on a wooden block on an insulating stool: it was principally from this that flashes sprang sometimes.)

FIG. 3.



The following readings give an idea of the range of adjustment permissible; all the flashes in a horizontal line occurring simultaneously:—

Length of Sparks (in inches).

A.	D.	F.	Jar lip.	Remarks.
0·48	0·53	0·48	Overflowed (4 inches).	
0·48	—	0·48	Quiet.	
0·48	0·42	0·37	Overflowed.	
0·69	0·32	0·45	Overflowed.	Here F began to fail.
0·69	1·03	0·0	Overflowed violently.	Here D began to fail.
0·69	1·03	0·9	Flashing from wood or anything.	Here F began to fail again, or to be replaced by other flashes.

Thus, with a long D spark, F could be anything up to nine-tenths of an inch; whereas, with a short D spark, it failed at half that distance. The jar-overflow is precipitated by a moderate A spark if D occur too. D can be much longer than A. If both A and D are long, the overflow is violent.

Larger Jar.

Now replace the first pint jar by one of the large "gallon" jars of similar open shape, but with the glass protruding 4 inches above the coatings, so that its overflow flash was 8 inches long.

(The capacity of the jar was 0·0062 microfarad.)

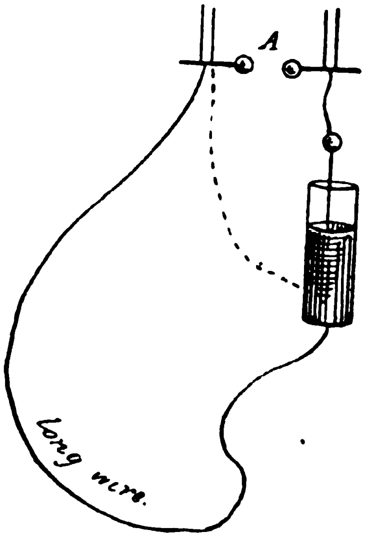
With A spark 0·62 inch long, the D and F gaps might be anything, but so long as the D spark was allowed to pass the jar overflowed every time the machine gave a spark at A.

On putting one terminal of the machine to earth (the one not attached to the jar), the D spark is considerably lengthened; and, even when the knobs are widely separated, brushes leap from each into the air whenever an A flash occurs.

Simplified Connexions.

5. Tried now this same gallon jar connected up to the machine in the simplest possible manner, either direct by a foot or so of ordinary wire, or else by the long thick copper round room or some other long wire, or sometimes by both, as shown in fig. 4, so as to see what difference the length of connecting circuit made to ease of overflow.

Fig. 4.



The machine's knobs were gradually separated until the jar flashed over its lip, and then their distance apart was read. It was found that with the long connector a very much shorter A spark was sufficient to cause overflow than with the short-circuiting wire. And not only was it shorter, it was incomparably quieter; the jar seemed to overflow without any trouble or violence when attached to the long circuit, whereas, when this was short-circuited out, the A spark had to be long to cause an overflow, and when it occurred its violence was great, as if threatening to smash the jar. If, under these circumstances, the short circuit was removed and the long wire replaced, the jar overflowed, not in one streak, but in a torrent or cascade of sparks; the number of these splashes gradually decreasing down to one again as the spark A was shortened.

It was also found that after an overflow another was more likely, whereas after a failure another failure was probable: that there was, in fact, a kind of hysteresis, the conditions of overflow being easier for a decreasing A spark than for an increasing one of the same length. This seemed especially noticeable when the long connector was thin copper, instead of being so thick and massive as the No. 1 copper on the one hand, or so highly resisting as thin iron on the other.

The table on p. 10 summarises the readings. The full contrast does not come out strong in the early numbers: there is some caprice about whether the jar overflows or not, probably having something to do with the state of the glass surface.

The contrast comes out best towards the middle of the table. The "thick copper" and other long wires are those specified in § 2.

Spiral Conductor.

6. Another connecting path was now made, consisting of 8 yards of the No. 1 copper wound into an open spiral about a foot in diameter, and suspended in air by ribbon, as indicated by the dotted line in fig. 5; when in use, its two ends were led, one to a machine terminal, the other to outer coat of gallon jar, whose inner coat was connected to the other machine terminal.

This being so, the lengths of machine spark needed to make the jar overflow (round its lip always) under different circumstances were again read as follows:—

	Kind of connector used.	Length of a spark needed for overflow.
Gallon jar.	Thick copper spiral	0·61 inch.
	Short circuit	1·50 „
	Spiral again	0·63 „
	Long thick wire round room	0·57 „
	Both this and spiral in series	0·56 „
	The two in parallel	0·62 „
	The spiral alone again	0·61 „
Pint jar.	Thick copper spiral	0·58 to 0·52 inch.
	Thick wire round room	0·51 inch.
	Spiral	0·53 „
	Short circuit	1·1 „
	Spiral	0·54 „
	Thick iron wire round room	0·66 „
	Iron and copper round room in parallel	0·62 „
	Iron alone	0·67 „
	Copper alone	0·52 „
	Short circuit	1·4 „
	Copper again	0·52 „

Connector used between machine and outer coat of jar.	Length of A spark able to make jar overflow (in tenths of inch).	Remarks.
Short wire	7·0	
Long thick copper wire	5·5	
Long thin copper wire	from 6·65 to 7·4	According to which it did last.
Long thin iron wire	7·8	
Short wire again	9·5	
Long iron shunted by short wire	11·5	No overflow.
Long iron alone	11·5	Still no overflow.
Thick copper again	6·4	Overflows every time until gap is shortened to this.
Thick copper shunted by short wire	17·0	Does not overflow till this long and noisy spark is reached.
Long thick copper alone	6·2	Still overflows even at this, the spark being gentle.
Retain thick copper. Earth one knob of machine	5·25	Jar still overflows.
Retain thick wire, but earth jar end of it	5·9	
Now earth machine end of it..	6·25	
Short circuit it once more....	17·0	Still does not overflow.
Simple thick wire alone once more	5·6	Overflows.
Thin copper wire............	min. 6·4, max. 7·1	A little indeterminate, according to whether overflow or failure happened last; that which happened last being easiest to get again.
Short circuit again	—	A has to be enormous before it overflows.
Thin iron wire..............	9·2	With this thin iron wire the overflow point seems definite, whereas with the thin copper it was not.
All three long wires in parallel	6·4	
Thick wire again, but with a bridge across trying to shunt out all but about 3 yards of it	6·5	
Short-circuit again added	10·3	
Remove the bridge but leave the short-circuit	from 8·7 to 10·2	No apparent reason for this shortness.
Disconnect one end of thick wire, but leave short-circuit	9·4	
Disconnect both ends, having only short-circuit	9·4	So now evidently the jar is easier to spark over, as it was at the beginning.
Restore thick wire simply....	5·5	

Effect of High Resistance.

7. Interpose the capillary liquid tube ($\frac{1}{4}$ megohm) in the circuit of the thick copper wire, putting it at one or other end of it, and the jar refuses to overflow, although the spark-length A is increased to $2\frac{1}{2}$ inches.

The spark is quiet, long, and zigzaggy. The resistance has the same effect at either end, but the spark seemed straighter when the resistance was at jar end of long wire.

To test effect of putting resistance into the *middle* of a long connector, both the thick wires round room (one copper, the other iron) were joined in series and used as connector. Overflow began when $A = 0{\cdot}6$ inch. The wires were now disconnected at their far ends, and the capillary tube made to bridge the gap. The jar now refused to overflow, though A was more than trebled in length. (Fizzing stopped it at that point.)

Contrast between C Path and Overflow.

8. But when an artificial overflow path is supplied to the coatings (as indicated by the strong line to a C knob in fig. 5) the matter is different. It does not now feel the effect of a long circuit as different from that of a short one. The space at C being 0·94 inch, a spark jumped there sometimes and sometimes at $A = 0{\cdot}75$, with the high resistance interposed in the two long leads; and just the same happened when the resistance was removed and the long wires directly connected.

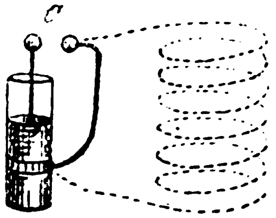
Shorten A to 0·64, and it was unable to select C, but it jumped the lip of the jar instead. It preferred 8 inches of jar-lip to 1 inch between the C knobs. When strong enough it would seem to go at C; when too weak for that it jumps the edge; but this is not a clear account of the matter. A better statement is the following:—

An A spark precipitates an overflow (*i.e.*, over the lip of the jar), but it does not precipitate a C spark. When a spark occurs at C there is quiet at A. The A and C sparks are alternative, not simultaneous. Moreover a C spark does not cause overflow. An A spark can easily occur without the edge of the jar being jumped, but the edge is never jumped without an A spark. (Connexions being as in fig. 4, with the addition of a short C or artificial overflow path, as shown by the thick line in fig. 5.)

Long Connector in C Circuit.

9. But now the thick copper spiral above mentioned (§ 6) was arranged to connect one of the C knobs with the outer coat of its jar

Fig. 5.



(as indicated by the dotted line in fig. 5; the strong-line shunt being removed), one of the two long thick wires round the room being used to connect up the machine to the same outer coat, as in fig. 4. Under these circumstances, simultaneous sparks *could* be got at A and at C, and both about the same length, but not when they are too long, say, A = 0·52, C = 0·57 inch. But now the jar can be made to overflow by either spark if of sufficient length. Thus if A = 0·61 or if C = 0·74, the jar lip gets jumped, and sometimes the A spark occurs, sometimes the C, but not both. Another reading: A = 0·69 or C = 0·94; jar overflows in either case.

Restore now the usual short wire to the C knobs, and the C spark still often goes, but it has no effect on the jar. The A spark makes the jar overflow as before.

But if the long lead between machine and jar be short-circuited-out (as by the dotted line of fig. 4), while the thick copper spiral still joins up to the C knobs (as indicated by the dotted line in fig. 5), then A cannot make the jar jump, while C can easily.

Thus overflow is always easily produced by the action of the spark occurring in a long good-conducting lead, not in a short or bad-conducting one.

Effect of Iron Core.

10. Using the thick copper spiral as before (§ 6) to make the pint jar overflow, I tried whether inserting large massive iron bars in it as a magnetic core would have any effect. There happened to be three large bars, each about 3 inches in diameter, which were used. They were of soft iron, and intended for the legs of an electromagnet.

No effect was found. The length of the A spark needed to make the jar overflow was, as near as one could tell, the same, whether the iron was in the spiral or not. Thus:—

Without iron	A = 0·53
With one bar in spiral	0·51
With three bars............	0·515

No difference that one could be sure of.

Effect of Capacity.

11. The spiral was now shunted out by a couple of Leyden jars in series, *i.e.*, with their knobs touching either end of it and with their outer coats connected. If the jars only touched one end of the wire, they had no effect; but when they touched both ends, a larger A spark was needed to cause overflow.

With the spiral alone .... A = 0·53
With the capacity shunt ..... A = 0·76

Experiments on Large Condenser.

12. It was not desirable to expose the large condenser § 1 to such conditions as would make it want to overflow, because overflow with it would mean bursting; but one of the pint jars was arranged on it as a safety valve, and it was then connected up to the machine. On now taking machine spark at A, the pint jar might or might not overflow its 4 inches.

With very short connexions ...... A = 0·5 inch did not overflow it.
With wires each a yard or so long.. A = 0·4 inch was sufficient.
And with spiral of thick copper... A = 0·3 inch was enough.

Iron Core Again.

13. Tried a stout spiral of brass wire (a spiral spring about a foot long and an inch diameter); it made the jar overflow fairly easily. Then inserted in the spiral a bundle of fine iron wires wrapped in paraffin paper, but could detect no difference whatever, *cf.* § 10.

Summary.

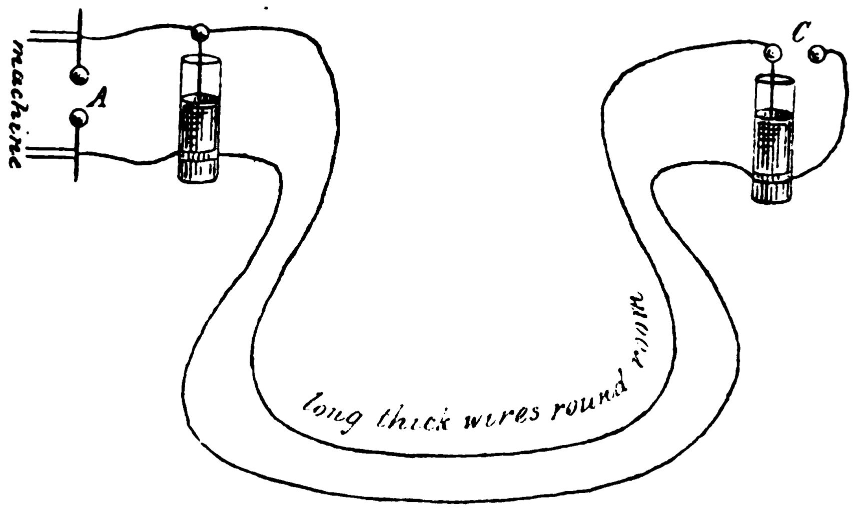
14. The noteworthy circumstance in all these experiments is the remarkable action of a long thick good conductor in causing the jar to overflow, especially if it be insulated, the most powerful conductor for this purpose being one with considerable self-induction and capacity but very little resistance. Evidently such a conductor assists the formation of an electric surging, whose accumulated momentum charges the jar momentarily up to bursting point. Resistance damps the vibrations down, and short wires have insufficient electric inertia and capacity to get them up. Iron, whether massive or subdivided, shows no effect whatever on the effective inductance of a circuit surrounding it.

It is also noteworthy how far more readily a jar overflows directly between its coatings over the lip than it does through a pair of discharging tongs held round the lip. Probably the sharp edges of the tinfoil contributed to this effect, possibly also dust or other specks on the surface of the glass, or it may be the action of the air film itself, but it seems as if the extremely small inductance of such a path likewise aids what, if it is to occur at all, must take advantage of a flood tide, a millionth of a second's duration.

CONFIRMATORY EXPERIMENTS (6th March, 1888).

15. Two similar jars, each with dischargers, were connected as shown in fig. 6.

FIG. 6.



A spark at A now caused the distant jar to overflow easily, but had no effect on the near one. Similarly, a spark at C caused the jar distant from C to overflow easily, but had no effect on its own jar.

An A spark never caused a spark at C. Sparks occurred either at A or at C, according to which happened to be the narrowest gap, but not at both; and it was always the jar most distant from the spark that overflowed its lip.

16. The explanation probably depends upon the fact that when a spark discharges its near jar the charge from the distant one rushes forward, but, not being able to arrive in time, surges back violently and overflows. The effect can probably be imitated with a long water trough by momentarily opening and suddenly closing a trap-door at one end. It can certainly be observed in a lavatory where there is a constantly dribbling cistern for flushing purposes. By opening and suddenly closing one of the wash-basin taps a surging is set up in the connecting pipe, and the dribble becomes a periodic for a second or two, in synchronism with the period of longitudinal vibration of the water in the pipe.

Something apparently of the same sort has been quite recently observed with sinuously alternating currents by Mr. Ferranti in the Deptford mains. But whereas that case can be described as a long stretch of capacity with locally concentrated inductance, mine is a long stretch of inductance with locally concentrated capacity. Accordingly, while he observes an extra current-amplitude, I observe an extra potential.

The phenomenon in another form seems to have been first observed by Sir W. R. Grove, and fully explained by Clerk Maxwell (see 'Phil. Mag.,' for March and May, 1868). It was subsequently rediscovered by Dr. Muirhead, and explained by Dr. Hopkinson ('Journn. S.T.E.,' 1884). A note sent by me to the 'Electrician' for 24th April, 1891, contains a summary of the history and explanation.

DISCUSSION OF OVERFLOW AND SURGING EXPERIMENTS.

17. For the complete explanation of the overflow experiments, the static capacity of the long wire, and the momentum of the pulses rushing along it, must be taken into account, and a wire is more effective when insulated and charged than when lying on the ground.

It does act, however, even when lying on the ground, *i.e.*, when its magnetic momentum is all that can be supposed effective. But the ordinary theory of discharge oscillation will not account for the jar being thereby raised to a higher potential than it was at the beginning of the series; the amplitude of the vibration necessarily decreases. Hence it is probable that the fact of overflow does not prove that the entire potential of the jar is raised; only that the potential of the tinfoil edges is excessive. The charge is probably not uniformly distributed at the extremity of each swing. The fringe of sparklings above the edge of the tinfoil are well known whenever a jar is discharged; and overflow is merely an exaggeration of these sparklings, which usually leap up and subside. In fact they can be seen to jump higher and higher, as the spark is gradually increased, until the lip is leaped.

The idea of the pulses rushing along the connecting wires, and adding their momentum to the oscillation of the jar-discharge, suggests that there must be a best length for the connectors, viz., when the period of their pulses agrees with the period of oscillation of the discharge; and the fact that there is a best length is found experimentally.

The same length of connector is not equally effective with pint and gallon jars. A longer one is best for the larger jar; and if a connector be too long it does not promote overflow any more vigorously that if it were somewhat too short.

The damping effect of resistance no doubt partly comes in here as helping to account for the evil of unnecessarily long connecting wires; and no fine adjustment of length has been found necessary to bring out in a marked manner the surging effects.

If any experimenter should fail to obtain these conspicuously, he probably has his connectors too short or too long. It is advantageous, though not essential, to have the long wire insulated. It is essential to have it highly conducting. Iron is for these purposes by far the worst conducting metal, because it is magnetically throttled

Another small point is that good contacts aid in causing overflow; especially when the connecting wires are not long enough. Insignificant air spaces suffice to damp out some of the vigour of the subsidiary oscillation to which these effects seem due. With long massive leads, however, good joints are not of so much consequence.

(Parenthetically it may be remarked how well adapted the usual orthodox lightning conductor is to develop violent surging and splashing effects.)

Further Overflow and Surging Circuit Experiments.

18. Two jars standing side by side, and connected in parallel by long wires to the machine, sometimes both overflowed. Sparks taken at the jar knobs with ordinary discharging tongs had no such effect.

The tongs were sometimes arranged over the lip of a jar, so as to help its overflow if possible; but it was not easy to do this. Near the edge of each coating they had the best chance, but the splash usually preferred an immense jump through air over a glass surface to a much smaller jump through the discharging tongs. Overflow is evidently a very quick effect, and must occur in a hurry or not at all.

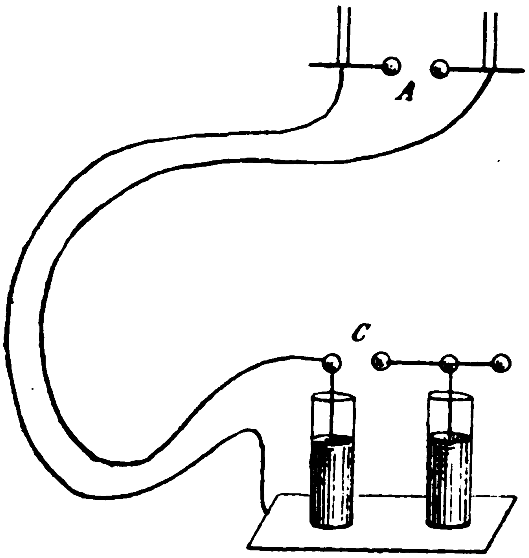
A couple of jars standing side by side on the same metal plate had a gap between their knobs as shown in fig. 7, and one of them was connected by long leads to the machine. It now often sparked across C into the second jar when an A spark occurred. But the second jar was not thereby charged. The charge just sprang into it and out again.

Connector without Self-induction.

19. Connected up a jar to the machine with a special anti-induction zigzag of tinfoil, folded to and fro in twenty long layers with several thicknesses of paraffin paper between. Could detect no effect on the jar overflow. It acted like a simple short circuit.

Tried, on the other hand, a high inductance coil, viz., the gutta-percha-covered bobbin of a Wiedemann galvanometer, with an iron-

FIG. 7.

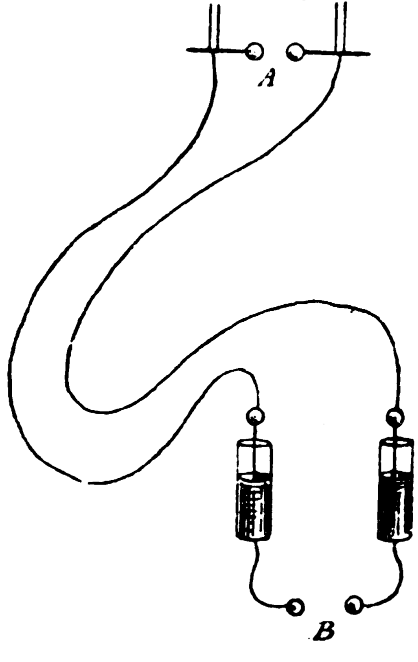


wire core inside: but its resistance was too high: it damped the oscillations.

Connector with Self-induction.

Interposed between machine and jars two thin wires round the room, and led the outer coats of the jars direct to a discharger, as in fig. 8.

FIG. 8.



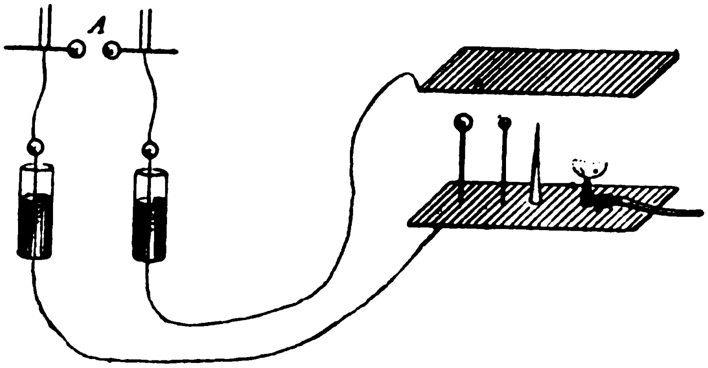
The jars being gallon jars, standing on wooden table. Compared A and B sparks; B was very long. Then substituted short wires for the long ones, and compared again. B was nearly as short as A. Readings follow :—

	Length of A spark.	Length of B spark.
Jars joined to machine by long wires ...	0·4 inch	2·2 inches
Short wires substituted	0·4 „	0·5 „

Overflow of Plate Condenser.

20. Connected a pair of tea-trays to the machine by long thick wires, and fixed them parallel to one another, keeping them asunder by glass or paraffin pillars; the jars standing on a wooden table, or being otherwise leakily connected so that they might charge. Every machine spark at A (fig. 9) caused long brushes, or sometimes remarkably long flashes between the plates.

FIG. 9.



A jar standing on bottom plate will receive a flash, but it will not necessarily be thereby charged; a slight residual charge may be found in it, but no more.

Points also get struck, just as noisily as knobs, and no more readily. Crowds of points, and knobs of all sizes, get struck equally well, if of the same height and all equally well connected to the bottom plate. The highest gets struck at the expense of the others. Often, however, several get struck at once. A gas-flame burning on the bottom plate gets struck at a much greater distance than does any metallic conductor. The weak hot-air column is precisely what this overflow discharge prefers. It takes it in preference to a metal rod of twice the apparent elevation, and strikes down right through the flame.

But though it thus readily smashes a weak dielectric, it will not take a bad conductor. A wet string or water tube may, in fact, reach right up till it touches the top plate, and yet receive no flash, while the other things shall be getting struck all the time.

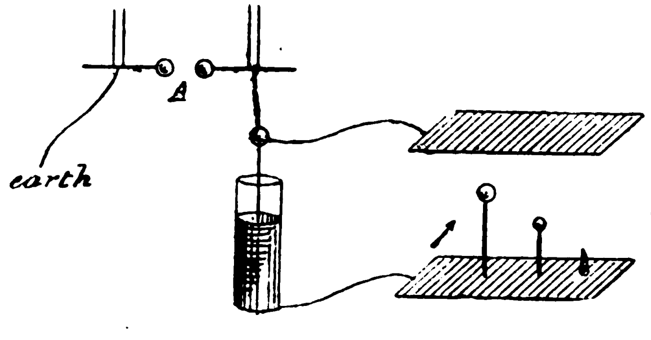
When the striking distance is too great for a noisy flash, a crowd of violet brushes spit between the top plate and protuberances on the lower plate: reminding one of some lightning photographs. The effect is still more marked if the top plate is a reservoir of water with a perforated bottom. The rain shower increases the length of these multiple gentle high-resistance purple discharges. Adding salt to the water tends to bring about the ordinary noisy white flash of great length.

Contrast between Path of Discharge under circumstances of Hurry and Leisure.

21. When the plates are arranged as in fig. 9, so that until an A spark occurs they are at the same potential and are then filled by a sudden and overflowing rush of electricity, all good-conducting things of the same height struck equally well, independently of their shape.

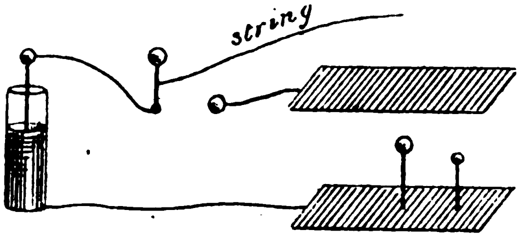
But when, on the other hand, the difference of potential between the plates was established gradually, as in fig. 10, so that the strain in the dielectric had time to pre-arrange a path of least resistance, then small knobs got struck in great preference to big ones, and points could not be struck at all, because they take the discharge quietly.

FIG. 10.



An intermediate case is when the charge and discharge of the top plate is brought about by pulling a lever over with string, so as to connect it with the jar, as in fig. 11.

FIG 11.



Sparking Distance between Plates in the Different Cases.

Terminal of rod standing on bottom plate.	Sudden rush caused by A spark, fig. 9.	Steady strain, fig. 10.	Intermediate case, fig. 11.
Brass knob 1·27 inch diameter........	0·93 inch	0·90	0·67
Brass knob 0·56 inch diameter.........	0·93 „	2·95	1·4
Brass point.........	1·03 „	At 6 inches it prevented discharge until covered up with a thimble.	—

Unless the jars are large, compared with the capacity of the plates, even the conditions of fig. 9 will not make the rush quite sudden; and in that case points and small knobs do get struck more easily than large knobs and domes, especially when the top plate is negative.* But when the rush is really sudden, no difference as to sign manages to show itself; and even such insignificant advantage as the point happens to show in the first column of the above table disappears.

High resistance, interposed between knob and bottom plate in fig. 10, alters the character of the spark entirely, making it soft and velvety, but has no effect upon its length nor upon the ease with which its knob gets struck as compared with others connected direct. But the same resistance, interposed in fig. 9, prevents its being struck altogether.

In other words, sudden rushes strike good conductors, independent of terminal: steady strain selects sharp or small terminals, almost independent of conductivity; the violence of the flash being, however, by high resistance very much altered. The total energy is, doubtless, the same, or even greater with the quiet heating spark, because of concentration and no loss by radiation; but the duration

---

* This fact has been explained by Mr. Wimshurst, 'Journ. Inst. Elec. Engineers,' 1889, page 482.

of the discharge is what makes the difference. The spark through high resistance, instead of being alternating, can be seen to be intermittent (*i.e.*, multiple), when analysed in a revolving mirror.

There is no need in these sudden rush experiments for the long leads of fig. 9, though perhaps they add to the length of the sparks.

22. Sparks thus obtained from the outer coats of jars are convenient for taking under water, or to water; and the phenomena thus seen are singular, and sometimes violent.

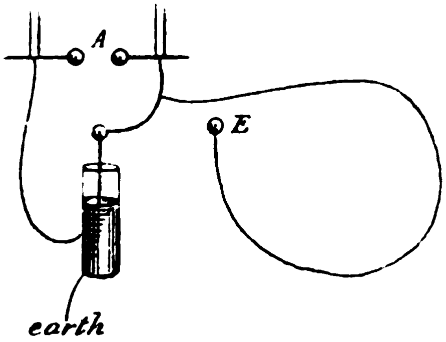
Water acts mainly as a dielectric under these circumstances, and, with small electrodes, such as the bared end of a gutta-percha wire, the water between gets burst with extraordinary violence: often breaking the containing glass vessel.

This arrangement of Leyden jars should be handy for blasting operations, because no specially good insulation of the leads is necessary.

EXPERIMENTS ON SURGING CIRCUIT PROPER.

23. Although all the overflow experiments are controlled by electrical surgings, I have been accustomed specially to apply the name "surging circuit" to the case where sparks are obtained not between two distinct parts of a circuit, but between two points on one and the same good conductor, under circumstances when it does not form the alternative path to anywhere, and when it would ordinarily be supposed there was no possible reason for a spark at all. For instance, in fig. 12 the loop of wire round the room is a mere off-shoot or appendage of an otherwise complete and very ordinary arrangement, and yet a spark can occur at E whenever the ordinary discharge occurs at A; a spark, too, often quite as long, though not so strong, as the main spark at A.

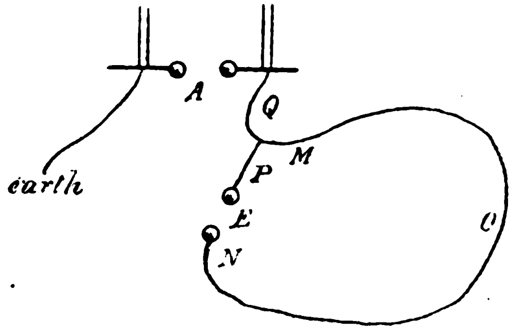
FIG. 12.



The jar is not essential to this experiment; and, in order to analyse it by inserting resistance at various places, it was modified to fig. 13, and the following readings taken: first, with a thin copper wire, and then with a thick copper wire, round room. The $\frac{1}{4}$ megohm liquid resistance could be inserted at either M, N, O, P, or Q.

The A knobs used were the small ones of a universal discharger, 1·4 cm. diameter, and 2·4 cm. apart all the time (equivalent to 1·5 cm. spark-length between flat plates). The E knobs were those of a spark-micrometer, and were 1·96 cm. diameter.

Fig. 13.



		Length of E spark.	Character of E spark.
No. 19 copper round theatre.	Resistance inserted at P	0·819 cm.	Weak.
	No resistance inserted anywhere	0·597 „	Strong.
	Resistance at P again	0·822 „	Weak.
	No resistance	0·555 „	Strong.
	Resistance at M	0·571 „	Strong.
	No resistance	0·571 „	Strong.
	Resistance at M again	0·571 „	Strong.
	Resistance at N	0·423 „	Very weak.
	Resistance at O	0·621 „	Strong.
	No resistance	0·536 „	Strong.
	Resistance at Q	No E spark at all, and A very weak.	
No. 1 copper round theatre.	No resistance	0·524 cm.	Strong.
	Resistance at N	0·379 „	Very weak.
	Resistance at M	0·638 „	Strong.
	Resistance at Q	No spark at all, and A weak.	
	Resistance at P	0·793 cm.	E weak but A strong.

This table evidently shows that the main part of the E spark is the rushing of the charge in the N part of the wire back to the discharged A knob. It has two paths, through the wire *viâ* O, and direct across the spark-gap E. Most of it chooses E, except when there is high resistance at N or P. Resistance at O interferes but little, and in fact it may help more across E; and resistance at M must certainly have this effect. Resistance at Q prevents any sudden effect of the A spark on the long circuit, and therefore never calls out a spark at E at all: the charged wire discharges leisurely through resistance at Q, and accordingly (there being no jar) the spark at A is quiet.

The fact in the table not immediately intelligible is the extra length of E spark caused by insertion of resistance at P; or, to a less extent, at O. It would appear to indicate the effect of surgings in the conductor, which accumulate a momentary opposite charge on one of the knobs before the one partitioned off by high resistance has had time appreciably to discharge.

EXPERIMENTS ON RECOIL KICK.

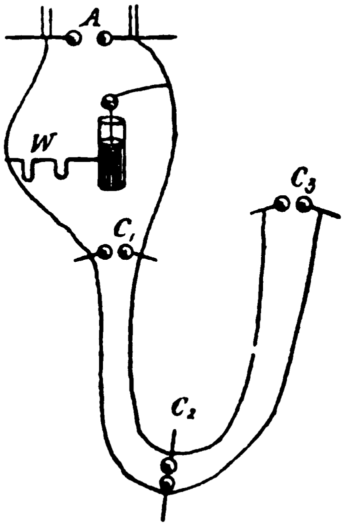
Early Observations (1 and 2 March, 1888).

24. Although the overflow experiments are evidence of the momentum of a reflected pulse, an idea which is intended to be conveyed by the term "recoil kick," yet I have been accustomed to apply the term specially to cases where reflexion takes place at the free end of a long wire, constituting an appendage or lateral extension, without forming any necessary part, of a discharging circuit. Usually a pair of similar wires were employed, and their ends were brought near enough for the momentum of the recoiling pulse, when spitting off from each wire, to bridge the interval and thereby cause a regular spark. If the wires were too far separate, a momentary brush leaped from each end and subsided again. Occasionally these brushes extended over a considerable length of wire, giving them a peculiar luminous appearance at each discharge. The fact that the brush was an up-rush and subsidence was shown by the similar appearance of both the wires, and by the fact that if a spark from either wire was taken into a jar the jar was not found to be charged by it.

25. The brush or sparking out from the wires, which I call the recoil kick, is most marked at certain places on those wires; and usually at the distant ends. This was what called attention to the effect (see above § 3). I find that Mr. A. P. Chattock obtained the first direct evidence of it, in some experiments with my apparatus which he made in my absence on March 1, 1888. The plan of the particular connexions used by him (fig. 14) has no importance, but it sufficed to show how much more readily a long spark could be obtained at the far end of long wires than at the near end; and Mr. Chattock was quite clear about the effect being due to reflected electric pulses or stationary waves in the wires, and was prepared to look for evidence of nodes and loops if the wires had been long enough.

In fig. 14, W is a high liquid resistance, the two long wires are the

FIG. 14.



thin copper and thin iron round room, and 1, 2, 3 are three alternative positions of a universal discharger, while A are the knobs of a Voss machine. Spark lengths are given in inches, but there is no importance in their absolute values.

Length of A spark needed to precipitate a spark between knobs of discharger *c* in its several positions.			Length of spark between knobs of discharger thus obtained. Called C.
Position 1.	Position 2.	Position 3.	
0·32	0·19	0·16	0·32
0·51	0·27	0·25	0·62
0·42	0·24	0·22	0·48
0·17	0·14	0·14	0·17

26. Next day I went on with these observations, replacing the liquid resistance W (which was useless) by a wire, and ordinarily using two jars in series instead of one, connecting their knobs one to each wire (more nearly as shown in fig. 15), and connecting their outer coats together and roughly to the earth by standing them on the same sheet of tinfoil on a wooden table. And because the knobs of machine and of discharger were not the same size, they were first compared by letting an ordinary discharge choose between them. They offered equally good paths when A = 0·45, C = 0·54 inch. The discharger was put in one or other of two positions: bridging

the long wires close to the jars (C_1), and bridging them at their far ends (C_3), fig. 14. The position C_1 manifestly does not essentially differ from A; the position C_3 is the interesting one. Of course if C were too short, the main spark occurred there instead of at A, but if the main spark occurred at A, a much longer supplementary or recoil kick spark often occurred at C_3, especially when the capacity of the jars and the length of the wires were suited to each other. As the following table shows:—

	Length of sparks.		
	A.	C_3.	C_1.
Without any jars	0·3	0·3	—
With small Voss jars	0·3	0·35	—
With pint jars (two in series)	0·24	0·42	—
Lengthen A till sparks just choose C instead	0·39	0·42	—
Shorten A till recoil sparks just fail at C	0·22	0·42	—
Get maximum C spark	0·42	0·63	—
„ „ „	0·45	0·75	—
„ „ „	0·45	—	0·47
Without any jars again (size of knobs accounts for this slight difference)	0·44	0·52	0·49
With the two pint jars, in parallel, shifted to the far end of wire near position 3, with overflow knobs to represent C_3	0·44	0·45	0·49
Same arrangement of jars shifted back to near position 1	0·44	0·78	—
Get the sparks at C_3 instead of as A	0·44	0·49	—
Arrangement as at first	—	0·49	—
Pair of gallon jars in series	0·45	1·09	—
Large condenser (0·02 mfd.)	0·45	0·59	—
	—	0·49	—

Thus the large condenser is as much too big as the Voss jars were too small. The gallon jars seem to show the effect best. They were therefore replaced, but this time insulated from the earth by standing them both on the same insulating stool with tinfoil top. Very long recoil sparks could now be got.

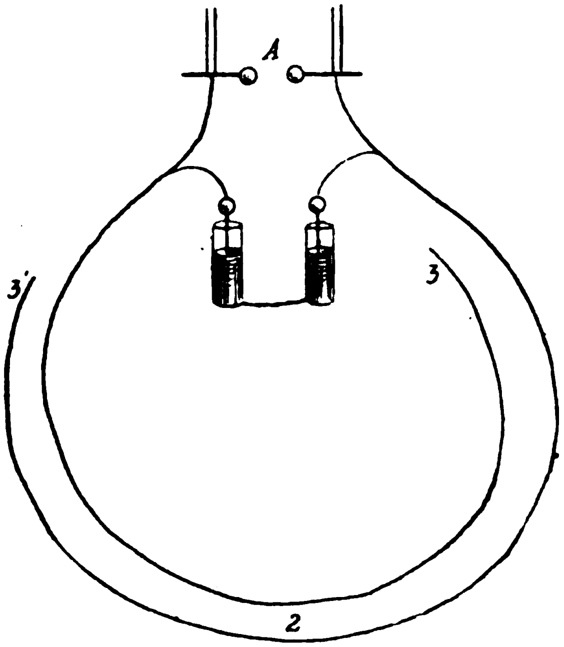
	A.	C_3.
Gallon jars in series on insulating stool	0·44	1·5
Another experiment	0·44	1·35
Big knobs put on the discharger	0·44	1·38

And at greater distances, when no regular spark occurred at C, there was still a brush discharge there at every A spark.

Joining up a small jar to the C_3 terminals, the long sparking and brushing there ceased.

Without this shunt jar, however, and with the terminals well separated, the wires glowed at every A spark along a considerable portion of their length, looking thick and fuzzy with momentary luminosity. (The wires were the long thin (No. 18 B.W.G.) copper and iron round the room: those two being up and handy for the experiment. They show the luminous appearance better than either thicker or much thinner ones.) With a small condenser the effect was not great, and with a very big one it was also not great; but with a single gallon jar the glow on the wires extended more than half way round the theatre, and a pair in series (*i.e.*, half the capacity) seemed to do even a trifle better.

Fig. 15



27. To see if the proximity of the opposite wires assisted the effect one of them was reversed, so that the plan was as in fig. 15; but the far ends of both wires got luminous as before (although the luminous portions were now on opposite sides of the room), and the luminosity extended from 3 to 2 on the one wire, and from 3′ to 2 on the other.

28. A jar was held in the hand near either glowing terminal, for the wires to spark into. They kept on doing so, but the jar was not charged, showing that they sparked in and out again.

This is characteristic of what I have elsewhere examined and called "side flash."

ESTIMATION OF WAVE-LENGTH.

29. Although there is nothing precisely metrical about these experiments, as so far conducted, it is well to notice that an approximation to the self-induction of the main discharge circuit can be obtained from them. For the capacity of the two gallon jars in cascade is about 28 K metres; and if the length of the wires which give the best recoil be taken as half a wave-length, the waves emitted are 60 metres long. So the inductance of the discharge circuit can be got from $2\pi\sqrt{(28\text{L}/\mu)} = 60$; whence $\text{L} = 3{\cdot}2\mu$ metres.

This is too small, showing that the waves are longer than 60 metres, and that the most appropriate capacity for these particular wires is something less than that of the two gallon jars in cascade.*

HISTORICAL OBSERVATIONS.

30. This evidence of the existence of electro-magnetic waves seemed to me of considerable interest, because I had been for some years contemplating the production of radiation by direct electro-magnetic experiments, the difficulty being their detection, *i.e.*, the proof of their existence.

My early notions, described to Section A of the British Association at York (1881), were directed towards the ambitious attempt of trying to make the waves short enough to be visible, at least to a thermopile or to some chemical detector. But two years later, at Southport, Fitzgerald pointed out that a discharging Leyden jar must emit radiation, and that though its waves would be yards or miles long, yet it might not be hopeless to prove that they were waves by obtaining interference phenomena.

Some of Lord Rayleigh's large-scale interference experiments with sound waves, exhibited to the Royal Institution on January 20, 1888 ('Nature,' vol. 38, p. 208), re-awakened in me the hope that such experiments were possible, and the desire to try them. And now, simply by attaching long wires to a discharging Leyden jar circuit, the waves had become without trouble conspicuous. One had only to lengthen the wires enough, and to look at them in the dark, to see by the brushes the nodes caused by the interference of the direct and reflected pulses surging to and fro in the wires; to see in fact the waves themselves, and to measure their length in a manner precisely analogous to the well-known experiment of Melde.

---

* [Or else that each wire behaves like an organ-pipe open at one end only, and so is a quarter of a wave long.—June, 1891.]

True that the Melde experiment does not measure the wave-length in air, and so also the observation of Mr. Chattock and myself would only measure the wave-length on wire; but it had already been shown by Mr. Heaviside among others, by Kirchoff also (though I did not know of Kirchoff's work), that pulses travelled along insulated non-magnetic wires at the same speed as waves through air, or at a speed only insignificantly less. In fact Mr. Poynting has taught us to regard all these effects as conveyed through the air, *i.e.*, by the ethereal medium, in a manner only very subordinately affected by the material of the conductor.

Hence the waves guided by long isolated wires and measured in recoil kick experiments ought to be the same length as, or only slightly shorter than, the true ether-waves spreading out from the oscillating circuit into space.

The fact that electric waves could be thus detected and measured, I stated at the Society of Arts, on March 17, 1888, and published more precisely in the 'Phil. Mag.' for August, 1888; but to this latter I appended a footnote to say that in the current number of Wiedemann's 'Annalen,' viz., that for July, the same year, there was a paper by Dr. Hertz, describing some experiments he had made at Karlsruhe, whereby he had detected the waves in free space: a research which in the following September was enthusiastically proclaimed to the world by Fitzgerald, at Bath. At the same meeting I described in general terms my detection of the waves on the surface of conducting wires. It appears that Hertz began, much as I had done, by the observation of surging circuits; for, using a coil instead of an inductive machine, and attaching to one terminal a nearly closed rectangle, he observed it spark across the gap. In this observation also he had the start of me, for his first paper appeared in 1887; and in his rapid development of it, in the comparative freedom from students of Karlsruhe, he struck on the influence between one circuit and another across space, and so made the astonishing discovery that the radiation in air was intense enough to cause sparks in conductors upon which it fell.

This same discovery would have been made by the audience at the Royal Institution on the evening of March 8, 1889, if it had not been made before; for, during a lecture on Leyden jars, every time one was discharged through a considerable length of wire, the heavily gilt wall paper sparkled brightly, by reason of the incident radiation.

The achievement of Hertz is well known, and it is only the customary interest attaching to circumstances connected with what will probably be regarded as an epoch in electrical science that constitutes my excuse for making the above statement.

One point, about which there has been some controversy, my experiments do make clear, viz., that the velocity of a pulse along an isolated thin copper wire is practically identical with the speed of light; in accordance with the theory based on Maxwell, and previously mentioned. Hertz at one time stated, as the result of some of his experiments, that there was considerable discrepancy between the speed of waves along wires and of waves in free space; and, though my own experiments were (to me at least) conclusive in the opposite direction, yet as they had not been published in detail, they could not be properly taken into account. The supposed discrepancy, however, had the good effect of leading Professor J. J. Thomson to make several interesting experiments.

QUANTITATIVE RECOIL KICK EXPERIMENTS (May, 1888).

Description of Wires used.

31. In order to make real measurements of wave-length, a circuit was carefully prepared, consisting of two copper wires (about No. 17 B.W.G.), 15 cm. diameter, stretched parallel to one another, half a metre apart, by silk suspenders.

They lay parallel to the theatre table, *i.e.*, north and south; but the room was not big enough for them to be wholly straight, so after travelling the length of the table horizontally they were taken a few feet vertically up, then back over head, and down again to the spark micrometer, according to the plan of fig. 16, nowhere being taken near any wall or other surface. Their total lengths were

$$1526+28{\cdot}5+16=1570{\cdot}5 \text{ cm.}$$
$$1529+36{\cdot}5+16=1581{\cdot}5 \text{ ,,}$$

so each may be taken as $15\frac{3}{4}$ metres long, and the wave length corresponding to their fundamental oscillation period as $31\frac{1}{2}$ metres, corresponding to about 10,000,000 vibrations per second.

When used alone, these are spoken of as "the shorter leads," because it was very soon necessary to supplement them by a similar pair of No. 17 copper wires half a metre apart, suspended similarly, but in an east and west direction, and used as extensions. When joined up in series with the former pair of wires the whole is spoken of as "the longer leads." The additional portions measured 2263 and 2247 cm. respectively. Hence the entire length of each of the longer leads may be taken as 38·2 metres, and the wave-length corresponding to their recoil as $76\frac{1}{2}$ metres, or say, 4,000,000 vibrations per second.

The total resistance of the "shorter leads" was 0·78 ohm, and of the "longer leads," 1·95 ohms.

The static capacity of the longer leads I estimate, by the formula

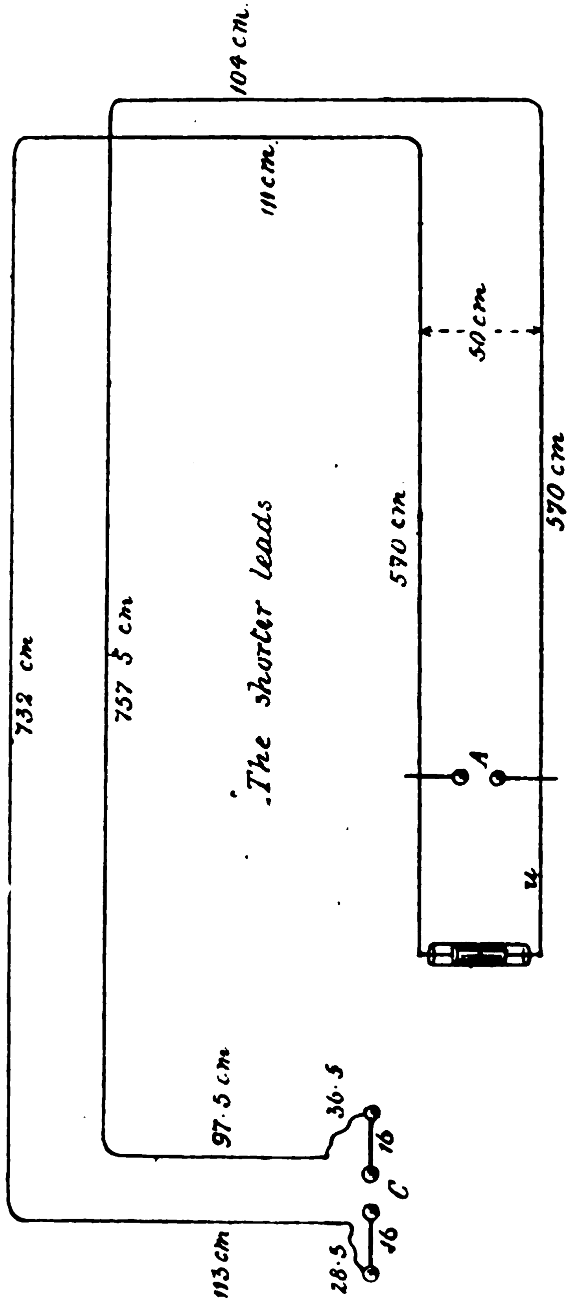


FIG. 16.

Kl÷4 log b/a, as 147 K cm. altogether, or K/26 per unit length; and their self-induction similarly, for currents which keep wholly to the outer skin, as 100,000 μ centimetres, or 26 μ per unit length. The electrostatic capacity of the "shorter leads" is 61 cm.

Plan of Experiment.

32. At the far end of these leads (either "the longer" or "the shorter") was arranged the spark micrometer, a micrometer screw

arrangement with millimetre thread, and head divided into 400 parts, made for reading Newton's rings, but supplied for present purposes with a pair of knobs 1·940 and 1·965 cm. diameter, on insulating glass pillars. These constitute the C spark gap at which the effect of the recoil kick is to be observed.

At the other end of the leads is arranged the condenser, usually a pair of jars back to back in one line, so as to close the circuit in a simple geometrical manner, and the Voss jars being at first used, *i.e.*, the small jars forming part of the Voss machine.

The A knobs at which the exciting spark is taken are constituted by the universal discharger, which, standing on a block under the two parallel wires above it, and connecting them together through an air gap, can easily be moved along the table to and fro, always in contact with the wires above it; and its distance from the jars at one end of the wires can be readily measured. This distance is called *u*, and is indicated in fig. 16.

The distance between the A knobs was supposed to remain constant, but to avoid any uncertainty, and to eliminate the effect of the different size of its knobs, the virtual length of the A spark was measured with the spark-micrometer by bringing its knobs near enough to just shunt out the discharger, so that half the sparks chose one and half the other. The distance between the C knobs under these circumstances is entered in the table as the virtual length of the A spark. They are then separated further, so that the spark occurs every time at A, but it does not cease at C until they have been widened distinctly. The maximum distance to which they can be separated without causing the C spark to altogether cease is then read, and the excess of the one reading over the other constitutes the "recoil kick." This procedure was then repeated for another position of the discharger A.

The plan of operation usually was to begin with the discharger close to the jars, and to move it away along the leads 5 cm. at a time, reading in each position the minimum and maximum C sparks, as just explained, the maximum reading being that at which C began to fail. Tuning is more easily done by thus varying the inductance of the discharge circuit than in any other way.

A short range would have been sufficient to give the position at which the maximum recoil kick occurred, but an extensive range was often used with the idea of getting indications of harmonics.

Measurement of Capacity of Jars used.

33. Rough estimates of the jars employed in this and similar experiments could be made in various ways, and no great accuracy is worth aiming at with ordinary shapes of jar, because of the difference between the circumstance under which they are used from those

under which they are measured. Nevertheless, in order to get a fairly good measure of their capacity, a standard condenser was made, with which they could be compared.

Standard Air-condenser.

A couple of plates of carefully selected plate glass, as used for mirrors, about 2 feet square, were silvered chemically on both faces, secure connexion between the two faces round the edge of the top plate being made. A circular cut or clean scratch, 1 mm. broad and 53·04 cm. inside diameter, was then made on the under surface of the top plate so as to isolate a trap-door portion. A hole previously drilled through the centre of the top plate, and silvered inside, permitted conductive access to the central area; and the borders of the plate acted as guard ring. The silver was cleared away from a small patch near the centre of the upper surface of the top plate, and a glass tube cemented on permitted the trap-door terminal to emerge in a well-insulated manner. Two other terminals, one attached to the bottom plate, and the other to the general surface of the top plate (the guard-ring terminal), were provided.

Four glass distance-pieces with wide bevelled edges (to improve insulation) were carefully cut out of one piece of glass, and their thickness was measured with a spherometer as 0·12083 inch.

The top plate was supported on these, near its four corners, and the whole placed in a suitable box with artificially dried atmosphere, the bottom plate being similarly supported near its corners, so that whatever bending there was might result in concentric surfaces. The electrostatic capacity of the trap-door was thus 572·9 cm.

There was some difficulty with the insulation of the trap-door portion, and the main leak was traced to dust, viz., fine fibres of some length, which settled on the bottom plate and bridged the interval between it and the top one. The narrow gap between trap-door and guard-ring, being of course carefully cleaned, was not found to leak anything like so much as one of these fibres. By care, the causes of leak could be minimised, and a special key was constructed whereby the trap-door could be discharged through a ballistic galvanometer the merest instant before the guard-ring was discharged to earth. In fact, by a screw adjustment the two events could be made simultaneous.

34. A set of 144 secondary Planté cells, made by bending strips of lead over small glass vessels standing in a sort of test-tube rack, having been charged in twelve sets of twelve each, were connected in series and used to fill the condensers with.

Sometimes different kicks were obtained with the whole series of cells; sometimes the same kick was imitated by tapping off a certain number of them, the same number being taken in different parts of the battery to secure fair uniformity.

The following are the estimates of capacity made from these observations, the standard air-condenser being taken as 573 cm.:—

Capacity Measurements.

	Electro-static capacity.
Two gallon jars in series	2800 cm.
One of them..	5640 „
Two pint jars in series	660 „
One of them..	1280 „
The other..	1360 „
One Voss jar	214 „
The other Voss jar................................	357 „
No. 1. Sliding tube-condenser; length in use 3 cm.	80 „
„ „ „ 6 „	120 „
„ „ „ 9 „	177 „
„ „ „ 12 „	226 „
„ „ „ 15 „	258 „
„ „ „ 18 „	290 „
No. 2. „ „ „ 15 „	272 „
„ „ „ 20 „	338 „
„ „ „ 28 „	450 „

The two jars supplied with the Voss machine happen to be, unfortunately, unequal. Their capacity in series was rather small to actually measure satisfactorily: so I take it as 134 cm.

First Approximation to Inductance of Circuit.

35. In order to estimate the inductance of the discharge circuit, it is necessary to know the following data:—

Thickness of the No. 17 wires........	0·15 cm.
Thickness of A discharging rods......	0·60 „
Thickness of rods inside Voss jars....	0·98 „
Thickness inside other jars	0·6 „

Now, the discharge circuit consisted of a rectangle with one pair of opposite sides made by certain length, *u*, of the No. 17 wires 50 cm. apart, and with the other pair of opposite sides made by discharge and jar rods, 50 cm. in length, and separated by a distance, *u*.

I am not prepared to calculate the inductance of this rectangle precisely, but when approximately square it makes but little difference whether I reckon it as a pair of parallel wires of length *u*, distance 50, and diameter 0·15, plus a pair of parallel rods of length 50, distance u, and diameter 0·8; or whether I reckon it as a circle of perimeter 2 $(50+u)$ and average thickness 0·3. For cases where the rectangle is elongated, the former approximation is best, so I use it in preference to the other always; reckoning the self-induction, therefore, as

$$L/\mu = 26u + 200 \log \frac{u}{0{\cdot}4} \text{ cm. } \ldots\ldots\ldots\ldots \quad (24),$$

Its real value will be somewhat greater than this.

36. In the following tables the experimental data were obtained and recorded carefully. The notes appended to each, concerning the amount of agreement between calculation and experiment, are capable of further refinement: but they suffice to show that the discrepancies between calculation and observation are as small as could be expected, and that, to a first approximation, experiment and theory agree; in other words, that if the velocity of a pulse, along thin isolated copper wires, differs from the velocity of light, it does not differ to any considerable extent.

RESULTS (12th May, 1888).

37. Two Voss Jars end to end, as shown, with "Shorter Leads."

Length u.	Min. C spark, *i.e.*, virtual length of A spark (in mm.).	Max. length of C spark (in mm.).	Excess of max. over min. (C—A) or recoil-kick (in mm.).
cm.			
5	9·15	—	—
10	9·10	—	—
15	9·05	9·39	0·34
20	9·10	11·25	2·15
25	9·00	11·27	2·27
30	9·05	12·00	2·95
35	9·26	12·90	3·64
40	9·26	11·09	1·83
45	9·22	10·20	1·98
50	9·29	9·38	0·09
60	9·15	9·24	0·09
90	9·25	9·60	0·35

Here the maximum occurs somewhere about the 35 cm. distance, probably on the hither side of it; so we may judge that the value $u = 34$ is about the place where the waves emitted agree with twice the length of the "shorter leads," *i.e.*, are 31½ metres long.

To see how this agrees with calculation, we must decide how much of the capacity of those wires ought to be added to the capacity of the jars in calculating the period of the discharge oscillation. If we include none of the leads in the discharged capacity, $S/K = 134$ cm.; if we include the whole, $S/K = 195$ cm.

As for the self-induction, we get that approximately by putting $u = 34$ in the expression (24), which gives it as 1768 cm.

So the calculated wave-length is, with the whole of the leads capacity, $2\pi\sqrt{(195 \times 1768)} = 3690$ cm. or 37 metres; and the agreement is not very good. If the leads capacity is not supposed effective in forcing the vibrations, its charge being merely forced to vibrate by the jar discharge, then the calculated wave-length is 31 metres, which is suspiciously accordant with observation.

38. Single Voss Jar,* still with "Shorter Leads."

Length u.	Virtual A spark.	Max. C spark.	Recoil kick.
cm.	mm.	mm.	mm.
5	9·00	13·70	4·70
10	9·11	12·68	3·57
15	9·07	12·01	2·94
20	9·03	11·66	2·63
25	9·10	11·50	2·40
30	9·10	11·20	2·10
35	9·12	11·32	2·20
45	9·11	11·45	2·34

Here the maximum is evidently off the scale; so that, to show it, the discharging circuit requires to be still further diminished in size: which is impracticable. As to calculated wave-length, the lowest estimate makes it 30 metres, when $u = 5$: the highest estimate makes it $32\frac{1}{2}$ metres, either of which is so far accordant with observation.

Two Pint Jars in Series, with "Shorter Leads."

Although the back kick was now fairly vigorous, no particular evidence of its being greater at one place than in another was observable. Evidently the leads are too short. Hence added the extensions already described (§ 31).

---

* Probably the one with the larger capacity of the two, but unfortunately not quite sure of this.

39. Two Pint Jars end to end, "Longer Leads" (14th May, 1888).

Length u.	Virtual A spark.	Max. C spark.	Recoil kick.
cm.	mm.	mm.	mm.
8	9·52	15·14	5·62
10	9·45	16·24	6·79
12	9·63	15·88	6·25
15	9·45	15·85	6·40
20	9·73	19·20	9·47
30	9·90	27·73	17·83
40	9·85	18·25	8·40
50	9·91	13·75	3·84
70	9·96	12·73	2·77
90	9·85	12·99	3·14
125	—	13·28	—

Here the sharpness of the maximum is so great as to make it probable that $u = 30$ happens to hit the right place pretty exactly.

The calculated wave-length for this value of u (remembering to substitute 0·3 for 0·4 in equation (24) because of the less thickness of these jar-rods) is $2\pi\sqrt{(1700 \times 721)} = 7000$ cm., or 70 metres; a trifle less if the leads capacity is omitted; whereas the double length of the recoiling wires indicates 76½ metres.

This is not very good, and I hope that better calculation applied to the data will give a better result. The self-induction as estimated is almost certainly less than the true: but how much less I am unable to say. Another uncertainty is the appropriate capacity of the jars for these high frequencies. It is not likely that the K for the glass will be just the same for 4,000,000 vibrations a second as it is under steady strain.

40. Single Voss Jar, with "Longer Leads."

(Knobs of discharger set exactly 1 cm. apart.)

Length u.	Equivalent of A Spark.	C spark.	Recoil.
cm.	mm.	mm.	mm.
5	9·27	13·38	3·41
10	9·26	15·20	5·94
15	9·30	16·57	7·27
20	9·50	14·42	4·92
25	9·50	13·88	4·38
30	9·43	13·41	3·99
35	9·56	13·40	3·86
40	9·52	13·60	4·08
50	9·50	13·63	4·13

Here the maximum is not quite so well marked, and it is a little uncertain on which side of the 15-cm. position it lies.

Take $u = 15$ however, and add the capacity of the leads, 147, to that of the jar, 357, and the calculated wave-length comes out 47 metres; or, without the capacity of the leads, $39\frac{1}{2}$ metres.

This is hopelessly different from $76\frac{1}{2}$ metres, but it is probable that it is the upper octave. To make the fundamental wave-length 79 metres would require u to be about 130 cm.

It is evidently desirable in these experiments that the jar capacity shall be much greater than the leads capacity; for when the two capacities are comparable in size, the recoil kick, although it still exists, has no very well defined maximum.

It would also be desirable in future experiments on the same plan to use, as dielectric in the condenser, a substance, like paraffin, whose specific inductive capacity may be depended on as fairly constant.

Experiments with Sliding Condenser.

41. The following experiments, made with an adjustable condenser, were intended to examine the effect of varying the capacity as well as the self-induction; also to see what evidence of harmonics could be detected.

The condensers used were each of them a pair of silvered tubes sliding into one another; their capacity, as the inner tubes were pushed into six different graduations, being measured above (§ 34).

The discharge circuit was a pair of No. 17 B.W.G. copper wires each 2 metres long, stretched horizonally on glass pillars, parallel to one another and 10 cm. apart. One of the tube condensers was arranged as a bridge at one end of these wires; and the discharger, with its knobs set 1 cm. apart, was used as a movable bridge and set at different measured distances from the condenser.

Charging from the machine was done through wooden sticks, so as not to introduce unknown capacities. The "longer leads" lead from the coats of the tube-condenser to the spark-micrometer, where the equivalent A spark and the maximum C or recoil spark were observed.

The numbers entered in the following table are the excess of the max. C spark over the virtual A spark, *i.e.*, C spark-length minus A spark-length, in millimetres. The maximum occurs in the different columns at about $u = 50$, say 35, 30, 25, 20, and 15, respectively.

42. Summary of Experiments with Tube-condenser No. 1.

("Longer Leads.")

Length of A spark mm.	9·57	9·32	9·32	9·5	9·5	9·57
	Recoil kick, or C − A (in mm.).					
Distance of A knobs from condenser (the length *u*).	3 cm. in use.	6 cm. in use.	9 cm. in use.	12 cm. in use.	15 cm. in use.	18 cm. in use.
cm.						
6	—	—	—	6·10	7·05	8·60
10	3·20	5·28	7·10	8·07	10·00	10·93
15	—	—	—	10·07	11·60	12·33
20	3·80	6·63	9·58	10·86	12·10	12·18
25	—	8·37	—	11·15	11·50	—
30	5·30	9·03	11·00	11·00	11·15	12·18
35	—	8·85	—	—	—	—
40	5·73	8·22	10·15	10·45	10·45	—
50	6·40	7·88	9·68	10·17	9·87	10·80
60	5·20	7·16	9·10	9·82	9·90	—
70	6·26	6·78	9·00	—	10·05	10·38
80	6·40	6·40	—	9·00	—	9·31
90	4·45	—	8·58	—	9·00	—
100	4·03	6·27	—	8·05	7·97	7·84
150	—	—	7·10	7·00	7·82	7·18

The readings were not all taken on the same day; and the length of the equivalent A spark, as read on different days, is recorded at the top of each column. The wave-length is the same in each case, and rough calculation makes it probably about 27 metres when the kick is at a maximum. This may be supposed to be the second harmonic of the vibration period of the long leads.

43. Summary of Experiments with Tube-condenser No. 2.

(“ Longer Leads.”)

Equivalent length of A spark, 9·22 mm. (June, 1888).

	Recoil kick, or C – A (in mm.).			
Distance of A knobs from condenser (u).	(1) 15 cm. in use.	(2) 15 cm. in use.	20 cm. in use.	28 cm. in use.
cm.				
5	6·04	6·68	8·18	9·65
10	9·00	9·18	11·04	12·28
15	10·35	10·78	11·90	12·48
20	12·05	11·52	12·18	12·28
25	10·90	11·15	11·25	11·90
30	11·43	11·19	11·23	12·08
40	10·20	10·93	11·04	12·78
50	10·15	10·35	—	11·89
60	—	—	10·43	10·70
70	9·68	10·35	—	10·03
80	—	—	9·73	9·22
100	8·28	9·03	8·18	9·48
120	—	—	8·98	10·03
130	7·15	8·58	—	—
150	6·34	8·28	7·35	10·33

The two sets with 15 cm. of the condenser in use are on different days, the only difference being that in (2) the discharge circuit was turned round 180° so as no longer to be beneath the longer leads at a possibly interfering distance. The absolute reading differs, but the maximum occurs in the same place.

The maxima in all this set are by no means well-marked, but there is an indication of a second maximum in the last column, at about $u = 40$; and of still another near the bottom. Taking the self-induction of the discharge circuit as $19\frac{1}{2} \times 45$, and the capacity of the jar as 450, the calculated wave-length for $u = 40$ comes out 38½ metres, or just the first harmonic of the leads-vibration.

The second harmonic occurs at $u = 15$; with wave length 26½ metres. There is a sign of another maximum near 150; and calculation places a fundamental vibration, agreeing in period with the leads, at about $u = 167$.