Further Researches on the Circular Spark

By

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§ 1. Introduction.

In the previous paper we have described the circular spark, a new type of phenomenon in the spark discharge. Yet there have been many untouched problems concerning it, such as the pressure effect, the relation between the circular spark and the matter of dielectrics, the effect of the frequency of the electric current, and so on. They are now investigated and some interesting results are obtained as following.

§ 2. Circular Spark by Reduced Pressure.

The apparatus of the experiments carried out at present is the same as that which was described in the preceding paper, to which is now added some requisites for reducing air as shown in Fig. 1.

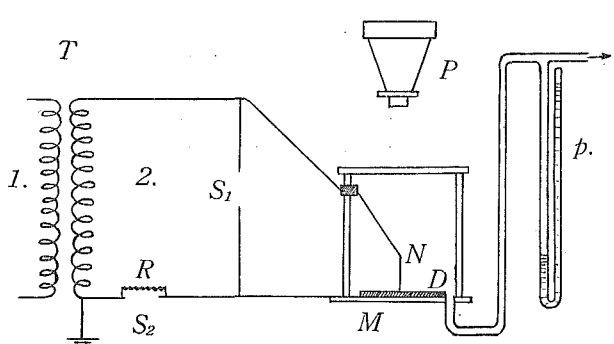

Fig. 1.

The main part of the apparatus consists of a circular cylindrical vessel of glass having both diameter and height of about 25 cm. The bottom of it is soldered to a thick brass plate by means of sealing wax.

Two series of experiments are made when using the transformer described in the previous paper and an induction coil with mercury interrupter keeping its frequency of interruption about 40 per second.

As dielectrics between the electrodes, a glass plate of 0.170 cm. thickness gotten from an Ilford photographic plate by washing off its gelatin film is used in one case and a common window glass of 0.175 cm. thickness in the other.

The results are given in Tables 1 and 2, and also shown in Figs. 2, 3 and 4.

TABLE 1.

No.	Air pressure in cm.	S_1 in cm. corr. to p.d.	Diameter of circle	Remarks
1	70.6	2.40	3.4 cm.	
2	64.7	2.51	3.7	
3	58.2	2.53	4.1	Decreasing pressure
4	55.0	2.65	4.5	
5	47.8	2.05	5.0	
6	39.0	2.50	6.5	
7	38.4	2.10	6.2	
8	29.4	2.35	8.0	
9	27.8	2.40	8.5	
10	34.2	2.30	7.2	
11	41.9	2.46	6.0	Increasing pressure
12	59.5	2.41	4.0	
13	66.3	2.50	3.6	
14	75.5	2.35	3.2	

Thickness of glass: 0.170 cm. Temperature of room: 23° C.
Using the transformer. Cycle of p.c.: 60.

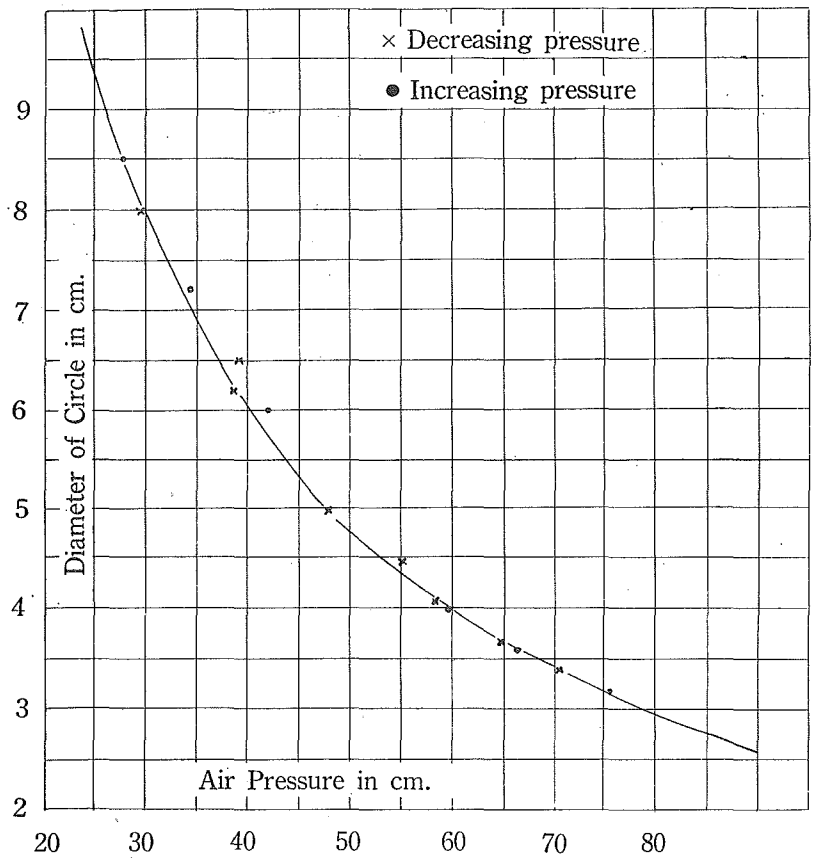

Fig. 2.

TABLE 2.

No.	Air pressure in cm.	S_1 in cm. corr. to p.d.	Diameter of circular spark
21	76.2	2.35	3.50 cm.
22	63.4	2.40	4.3
23	55.0	2.50	4.8
24	50.1	2.80	5.6
25	43.6	2.80	6.0
26	36.4	2.80	7.0
27	30.0	2.58	8.0
28	24.8	2.35	9.0

Ordinary window glass. Thickness: 0.175 cm.
Temperature: 23°C.
Using the induction coil. Cycle: 40.

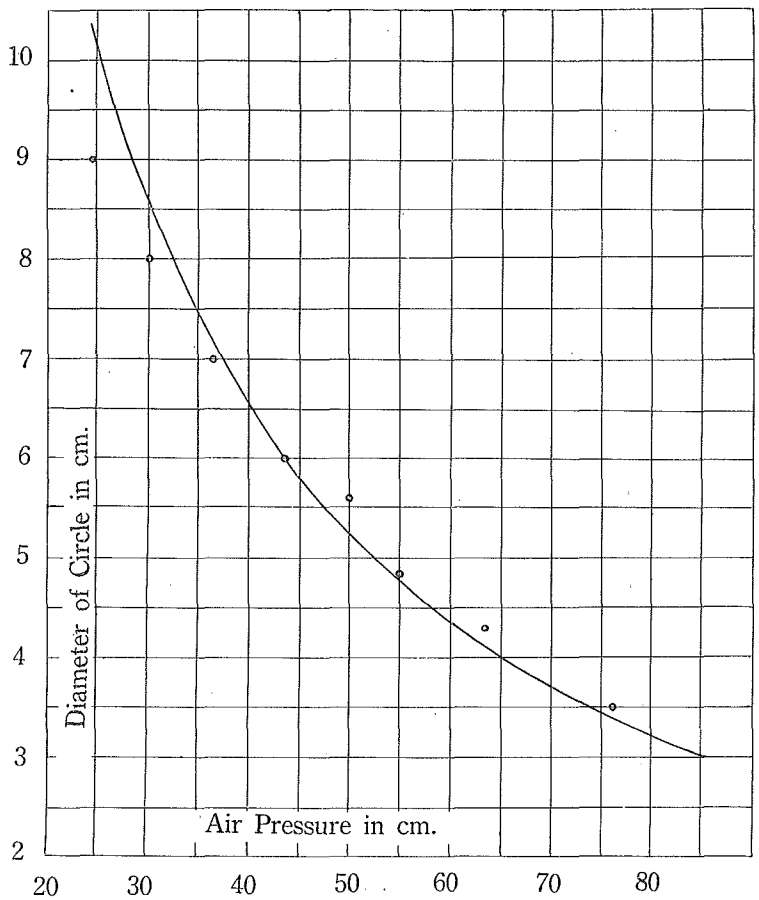

Fig. 3.

We see from these Tables and Figures that the diameter of the circle increases regularly as the pressure of the air decreases almost in a similar manner for both cases.

From the figures, we obtain the following experimental formula,

$$D \cdot p = k,$$

where k is the constant due to the thickness of the dielectric plate and its matter.

In the present experiment, $k=240$ for the former case, and $k=260$ for the latter. The continuous curves in the above Figures are drawn after

this formula. The result of the experiment coincides with this simple formula very well in the former case, but there are some deviations in the latter, especially in lower pressures.

The difference of the diameter of the circle for both cases is somewhat larger than expected from the thicknesses of the glass plates. It is due rather to the matter of each glass than to the primary current or to its frequency. These circumstances are also investigated and will be described later.

We remark here also about the formation of the circular spark. The formation of the fine circle in a closed vessel seems to be much disturbed by ionized gases which have been produced during the discharge. Hence after regulating the primary current and the series spark gap in the secondary circuit, it is better once to renew the air in the vessel and reduce its pressure again to the former value.

We remark further that it seems to be practically impossible to produce the complete circle in reduced pressures and we must be satisfied with the circularly refracted portion of the radiated spark. (Fig. 4).

§ 3. Discharge Figure at More Reduced Pressure.

At an air pressure of a few cm. with a certain proper distance of the series spark gap, there appears such a beautiful figure all over the glass surface that some luminous and dark canals radiate regularly from the centre. The canals have a brilliant colour commonly seen in the discharge at low pressure.

This figure can be made constant in its structure by adjusting the series spark gap, but for distances of the gap other than a certain value, the figure becomes quite unstable and even vanishes.

It is also necessary that the current be alternative; if not, say rectified by kenetron, no such figure appears.

The appearance of this figure is something like the negative Lichtenberg figure on a photographic plate, but the scale of the figure is much larger as shown in Fig. 5.

The number of dark canals depends on the thickness of the dielectric plate, the thicker the plate, the less the number of canals.

The frequency and the wave form of the current seems to have little effect on the form of the figure.

The potential difference between the electrodes is much smaller than in the case of ordinary atmospheric pressure, for the most part of the current flows over the surface of dielectrics and the small part flows through it.

Thus we see some coincident relations between this figure and the circular spark.

No. 1 in Fig. 5 is a result gotten with an ordinary glass plate of 1.20 cm. thickness, when the transformer is used, and No. 2, that with the same plate when the induction coil is used. We see that both are very like in their appearance except that the latter shows itself very slightly less steady than the former.

TABLE 3.

No.	Air pressure in cm.	S_2 Series spark gap	S_1 //le spark gap (p.d.)	Frequency of primary current	Remark
1	3.7	0.032 cm.	0.3 cm.	60	Transformer
2	4.2	0.062	0.2	28	Induction coil

Thickness of glass plate: 1.20 cm.
Temperature: 23°C.

§ 4. The Effect of the Frequency of the Primary Current.

To investigate the effect, we have made experiments by using the transformer with the primary current of 60 cycles and the induction coil with mercury interrupter. The frequency of interruption of the latter can be varied at will by regulating the speed of the motor.

Two series of measurements are made with different kinds of glass plate.

TABLE 4.

No.	S_1 Parallel spark gap	Frequency of primary current	Diameter of circle	Remark
1	2.3 cm.	60	3.2 cm.	Transformer
2	2.5	40	3.2	Induction coil
3	2.58	20	3.25	,,
4	2.38	21	3.3	,,
5	2.3	10.5	3.3	,,

Glass gotten from "Ilford" plate. Thickness: 0.170 cm.

TABLE 5.

No.	S_1	Frequency of primary current	Diameter of circle	Remark
1	2.90 cm.	19.7	3.75 cm.	Induction coil
2	2.60	39.3	3.60	,,
3	2.53	23.7	3.75	,,
4	3.10	11.5	3.64	,,
5	2.30	60	3.70	Transformer
6	2.30	60	3.71	,,

Ordinary window glass. Thickness: 0.173 cm.

Photographs of figure 3 in the latter are shown in Fig. 6.

The above results show that the diameter of the circle is independent of the frequency of the primary current and not effected by different sources of current which will cause different wave forms of current in the secondary circuit.

The distance of the parallel spark gap which corresponds to the potential difference between the electrodes seems to become slightly larger when the frequency is small.

§ 5. Effect of the Series Spark Gap in Producing the Circular Spark.

The series spark gap in the discharge circuit plays, as we have already briefly set forth, an important service for making the spark circular and there exists only one width of the gap to satisfy the condition for a given dielectric plate.

To show the circumstance more precisely we have taken a series of photographs with the same dielectric plate at various widths of the gap in question. The results are given in the following Table and in Fig. 7.

TABLE 6.

No.	Distance of series gap in cm.	//le spark gap in cm. (Corr. to p.d.)	Remarks
1	0.000	2.10	No spark, faint blow at the end of the needle.
2	0.020	2.90	No spark, very strong blow from all parts of the needle.
3	0.200	2.65	Spark sometimes appears, strong blow at the end of the needle.
4	0.350	2.35	Radial sparks refracting at random, weak blow at the end of the needle.
5	0.500	2.40	Radial and circular sparks but very unstable, faint blow at the end of the needle.
6	0.700	2.38	Stable and the finest circle.
7	0.900	2.20	Unstable and incomplete circles.
8	>1.000		Radial sparks only.

Window glass used with reduced pressures. Thickness: 0.175 cm.

It is most convenient that the diameter of the circular spark in each stage of the series gap seems to be apparently the same. In the present case the diameter of the circle is 3.5 cm. as seen in Fig. 7.

The circumstances described above are almost the same in the case of a reduced pressure.

The proper distance of the series spark gap increases commonly when the thicker dielectric plate is used, but this relation does not hold so exactly as to be represented by a smooth curve. In the sphere of our experiments the proper distance of the spark lies between a very short distance other than zero and one or two centimeters.

§ 6. Experiment with Sealing Wax.

In order to investigate the phenomena with different substances other than glass or mica with which we have already made some experiments, the author took sealing wax next; for this material has most of the necessary properties for the experiment as

1. to be an insulator or very bad conductor,
2. hard,
3. having a smooth surface,
4. having uniform thickness and sufficient area.

Plates of sealing wax of various thickness were obtained by stretching the melted wax (of a temperature just higher than its melting point) with a brass stick and a brass plate. The plate of sealing wax thinner than 0.05 cm. is very difficult to prepare, and besides such a thin one is very fragile when the spark discharge occurs on it.

In the experiment the induction coil previously mentioned is used for the following reason:—

The plate of sealing wax is easily broken or likely to be influenced by the spark when the transformer is used, but the plate is not broken when the induction coil is used. It must be due to the difference of electric current through the dielectric plate in each case, notwithstanding that the potential differences on both sides are of the same amount.

The approximate relative amount of the current has been measured by observing with a rotating mirror or through a photographic shutter the fluorescent spots on the screen of Braun's cathode ray tube which has been connected parallel to the series spark gap. It is observed that there are more than fifteen spots in a cycle of the tube when the transformer is used, but only two or three for the induction coil. This must show that the frequencies of sparks, that is the electric currents here, are proportional to

$$15 \times 60 = 900,$$

for one case, and

$$2.5 \times 60 = 150,$$

for the other.

The result of the measurement thus carried out is given in the following Tables 7 and 8, and also shown in Figs. 8, 9, 10.

TABLE 7.

No.	Thickness of wax plate	S_1 Parallel spark gap	Pot. diff. between electrodes	Frequency of primary current	S_2 Series spark gap	Diameter of circle
1	0.046 cm.	1.5 cm.	17 K.V.	40		2.4 cm.
2	.053	1.5	17	40		2.5
3	.055	1.5	17	40		2.2
4	.059	1.47	16.7	42.6	.354 cm.	2.98
5	.062	1.5	17	40		2.5
6	.096	1.96	22.0	42.6	.392	3.40
7	.105	2.05	23.1	,,	.424	3.30
8	.115	2.1	23.5	40		3.65
9	.138	2.20	25.0	42.0	.504	3.79
10	.140	2.46	27.3	42.6	.436	3.78
11	.183	2.98	32.5	42.0	.644	4.12
12	.185	2.80	31.0	,,	.648	4.18
12′	,,	2.77	30.7	,,	.680	3.95
13	.213	3.3	35.5	41.0	.700	4.27
14	.260	4.36	44.2	42.0	.864	4.77
14′	,,	,,	,,	,,	.850	4.68
15	260	4.6	46.0	41.8	.812	4.6
16	.460	6.6	59.0	40		5.25
17	.490	7.4	63	,,	1.50	5.5
18	.720	8.6	69	,,	1.8	6.2

Temperature: 23°C.

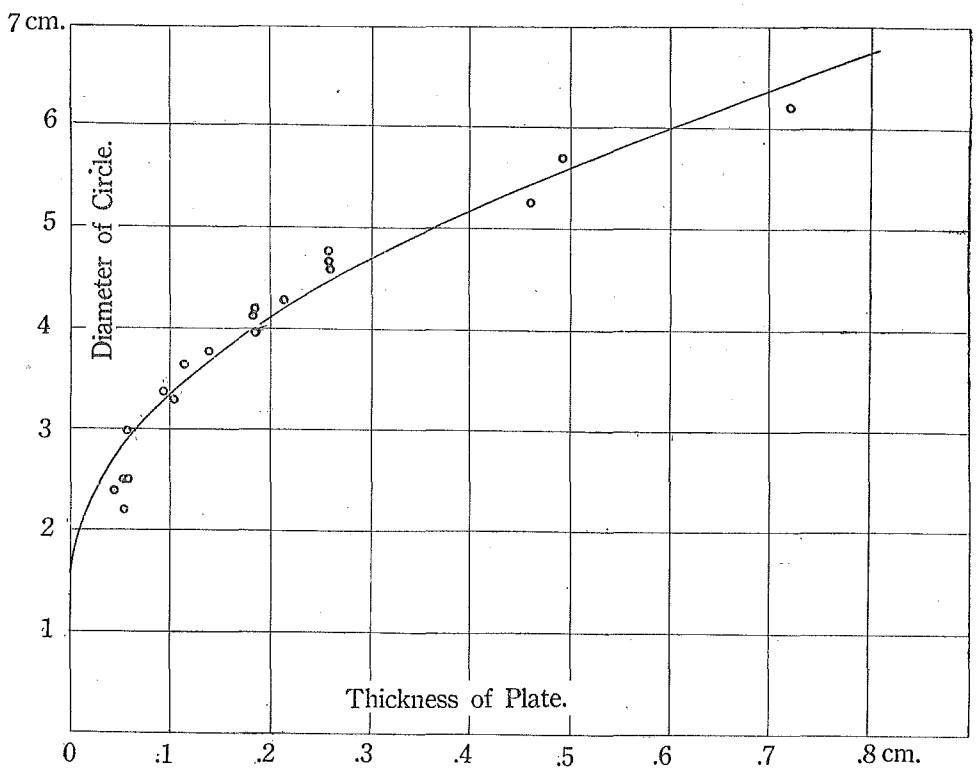

Fig. 8.

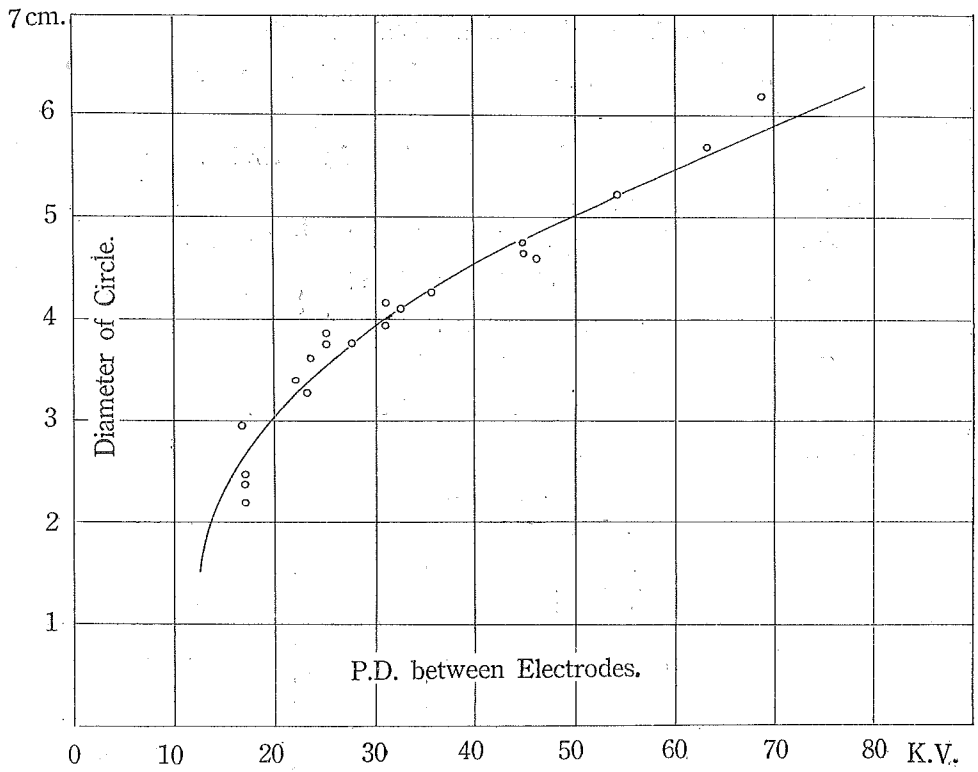

Fig. 9.

The diameter of the circle varies parabolically with the thickness of the wax plate just like the case with mica and glass, but the diameter of the circle with the former is fairly greater than that with the latter for the same thickness.

The relation between the diameter of the circle and the potential difference on both sides of the dielectrics is approximately parabolic, but there are some deviations in the cases of the thicker plates.

§ 7. Circular Spark with Various Substance and Relations between the Circle and Other Physical Constants.

The author has made, besides the above, a few researches on the circular spark with plates of different substances, namely glass, mica, sealing wax, ebonite, shellac, rubber, porcelain, wood, bakelite and others.

The beautiful circular spark such as obtained with glass or mica can not be obtained with the other substances, but their diameters are more or less accurately measured.

For convenience of comparison of the size of the circles, they may be classified into three as follows:

A: smaller than that obtained with mica and glass,

B: greater than that obtained with mica and glass, but smaller than that with sealing wax,

C: greater than that obtained with sealing wax.

The results are summed up in Table 8 and in Fig. 11, and some of them are shown also in Fig. 12.

TABLE 8.

Dielectrics	Thickness of dielectric plate	S_1	Diameter of circular spark	Greatness of circle	Dielectric constant	Remark
Glass (1)	0.285 cm. .35	2.97 cm. 4.6	3.75 cm. 4.15	— —	7.0	T. I. C.
Shellac (2)	.223	2.6	3.9	B	5	I.C.
Ebonite (3)	.330 .390	5.0 5.6	5.7 6.2	C C	2.55	I. C.
Bakelite (4)	.315	4.9	4.65	B		I. C.
Porcelain (5)	.60 .65	6.0 6.3	6.1 6.4	C C	4.4	T.
Rubber (6)	.28 .45	3.2 5.0	4.2 5.5	B C	2.73	I. C.
Celluloid (7)	.105	2.2	3.2	B	6.7	I. C.

T.: Using the transformer, (60 cycles).
I. C.: Using the induction coil, (40 cycles).

The sixth column in the above table is given here again from Landort-Börnstein's „Physikalisch-Chemische Tabellen".

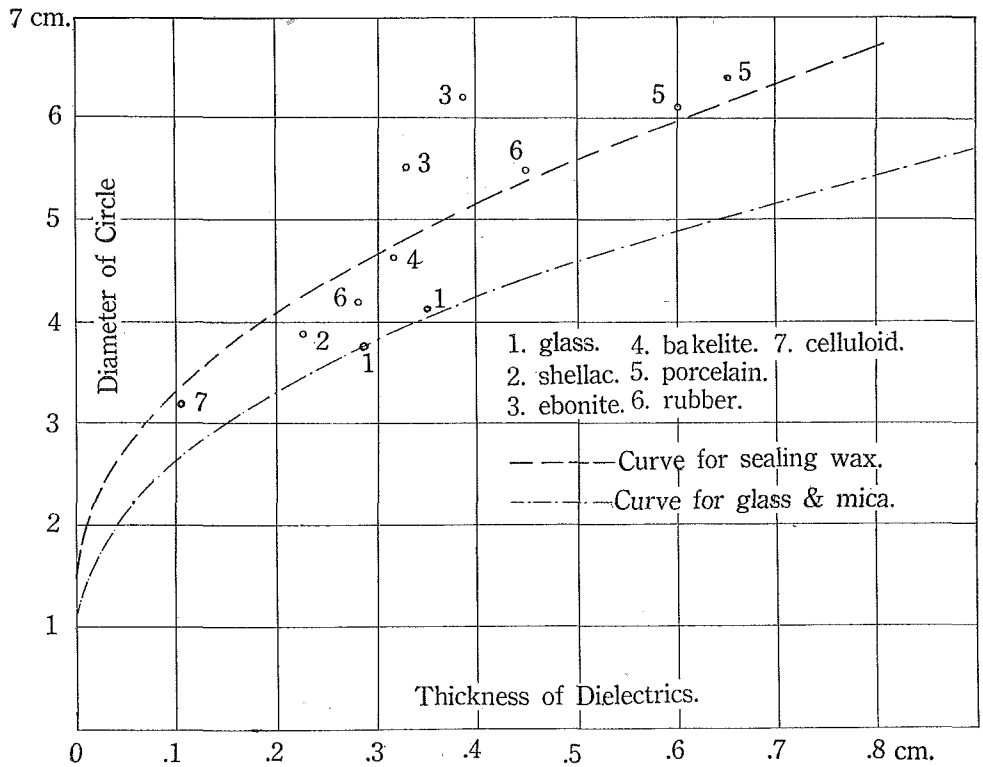

Fig. 11.

From the above results we can say approximately that the diameter of the circular spark formed with the various substances is larger when the dielectric constant of the substance is large. The parallel relation is also seen between the circular spark and the electric resistance (inverse to the specific conductivity) of the dielectric plate.

In order to determine if the above relations (among the diameter of the circle, the dielectric constant and the electric conductivity of the substance) explain the difference of the size of circular sparks on different plates such as shown in § 2 and § 4, we have made some measurements with four plates of different glass.

Instead of measuring the dielectric constants of these plates, the refractive indices are measured simply by means of a sliding microscope.

The exact determination of the electric conductivity under various conditions is by no means simple. At present the relative values of specific resistances have been measured by a certain preliminary method in order to know the mere difference in the physical properties among the plates.

TABLE 9.

No. of glass plate	Thickness of plate	Diameter ot circle	Dia. of circle reduced to .1 cm. in thickness	Refractive index	Relative elect. resistance
1	0.170 cm.	3.12 cm.	2.65 cm.	1.54	0.735
2	.173	3.70	3.02	1.52	.919
3	.185	3.45	2.83	1.54	.784
4	.142	3.50	3.15	1.46	.902

The fourth column in the table represents the value of the diameter of the circle which corresponds to the thickness of 0.1 cm. for each plate assuming

$$(D-1.1)^2=\alpha\times l,$$ [1]

where

D : diameter of the circle,

l : thickness of the dielectric plate,

α : parameter due to the plate.

We have find no striking difference of refractive indices among them except the last one, but some difference of electric resistance which proves positively the above mentioned relation between the size of the circular spark and the specific resistance of the plate.

Fig. 13 is the photograph carefully taken for each glass plate under examination.

In conclusion, the present writer wishes to express his best thanks to his friend Prof. Y. IKEDA for the continual encouragement given to carry out this work. His thanks are also due to Mr. K. YOSHITAKE who helped him during the whole experiment.

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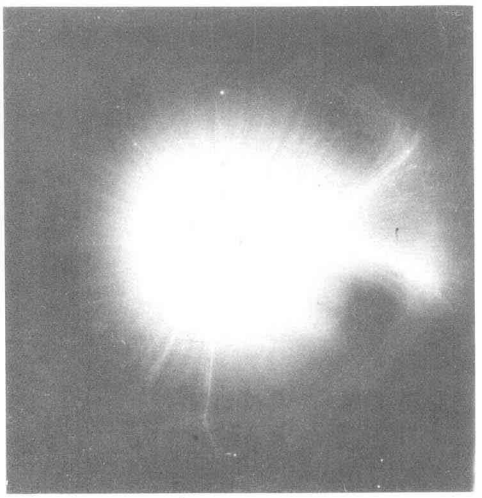
1) See page 112.

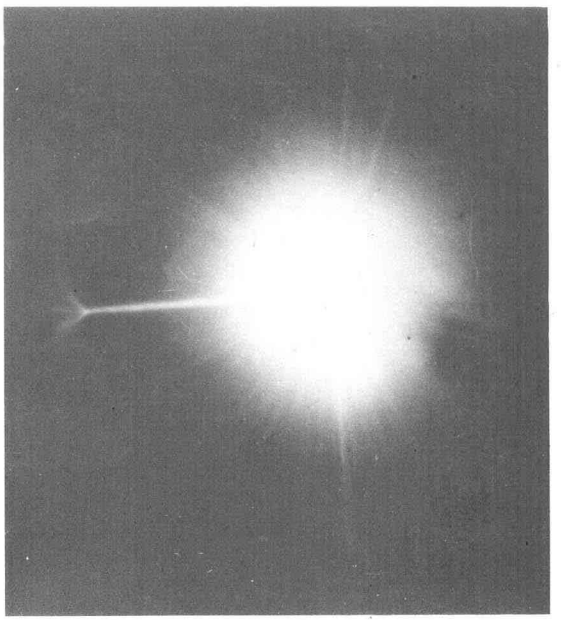
Fig. 4. Circular spark in lower pressures with glass plate.

No. 23 ×1



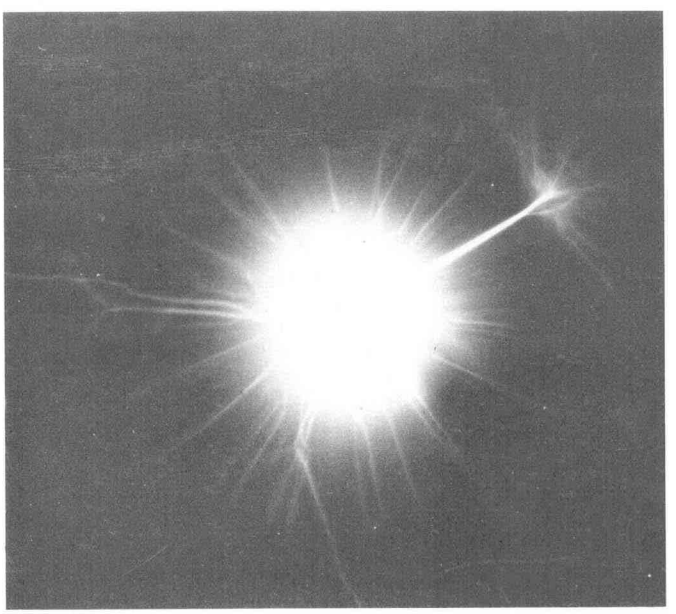
l=0.175 cm.
Press.=55.0 cm.
Using the induction coil.
(Cycle: 40.)

No. 6 ×1



l=0.170 cm. Press.=39.0 cm.
Using the transformer.
(60 cycles)

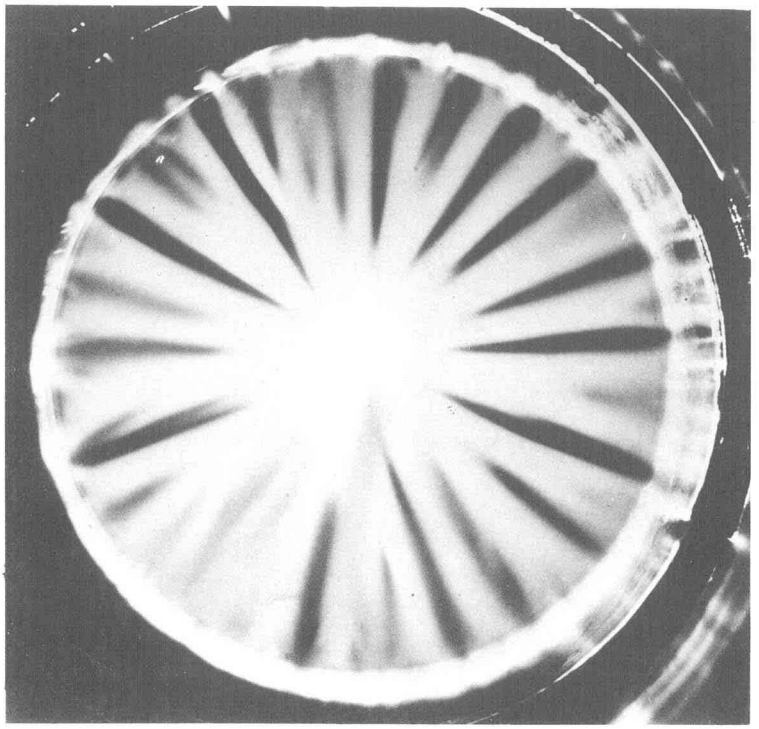
No. 7 ×1



l=0.170 cm.
Press.=38.4 cm.
Using the transformer.
(60 cycles)

Fig. 5. Discharge figure at more reduced pressure.

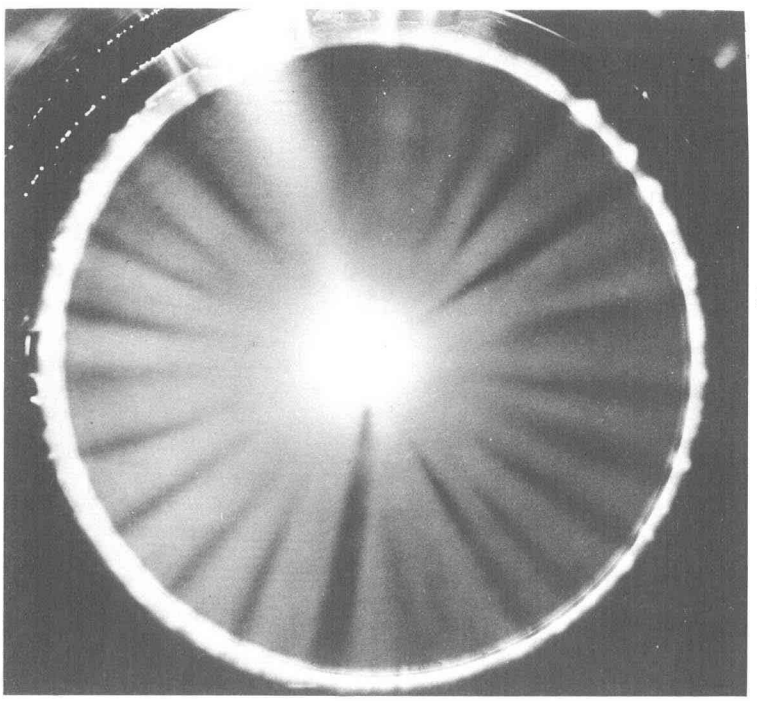
(1)



$\times \frac{1}{2}$

l = 1.2 cm.
Press. = 3.7 cm.
Transformer
(60 cycles)

(2)

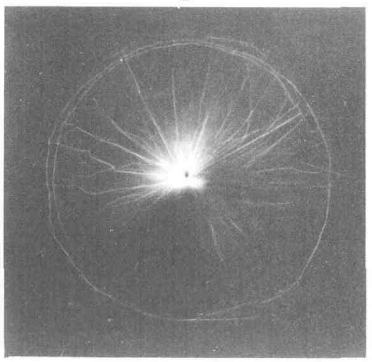


$\times \frac{1}{2}$

l = 1.2 cm.
Press. = 4.2 cm.
Induction coil.
(28 cycles)

Fig. 6. Effect of the frequency of the primary current on the circular spark.

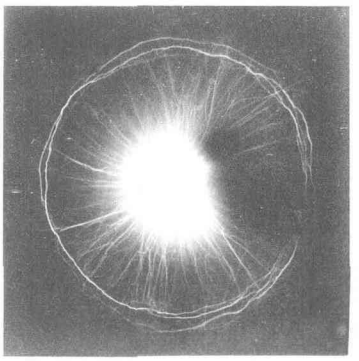
1



× 1

Induction coil.
(Freq. 19.7)

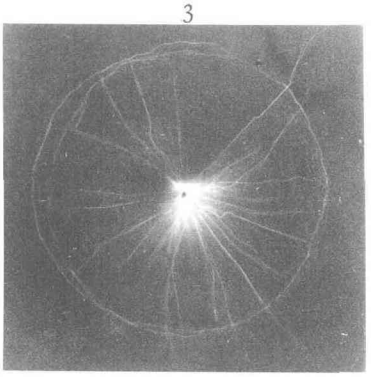
2



× 1

Induction coil.
(Freq. 39.3)

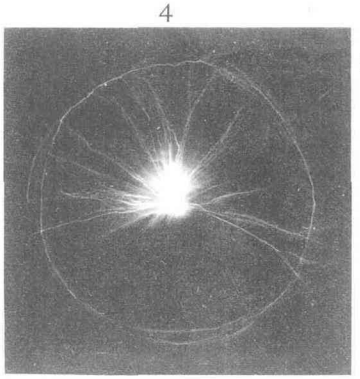
3



× 1

Induction coil.
(Freq. 23.7)

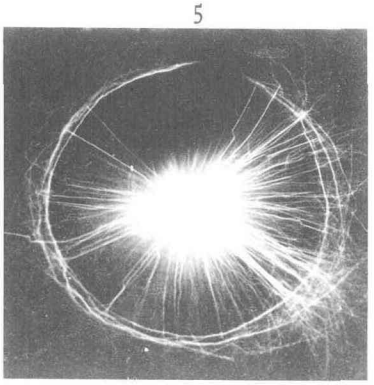
4



× 1

Induction coil.
(Freq. 11.5)

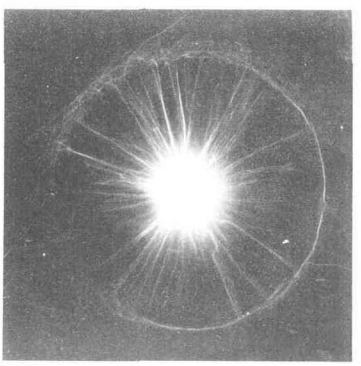
5



× 1

Transformer.
(Freq. 60)

6

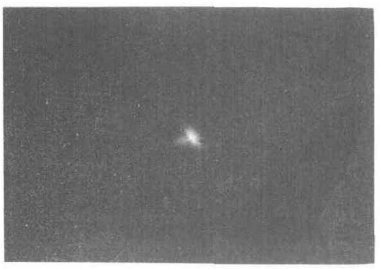


× 1

Transformer.
(Freq. 60)

Fig. 7. Spark figure at different widths of the series spark gap.

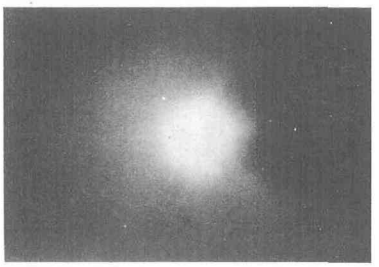
1



× 1

$S_2 = 0.00$

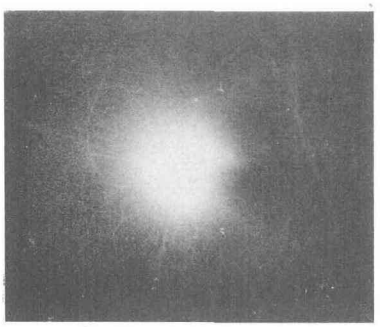
2



× 1

$S_2 = .020$ cm

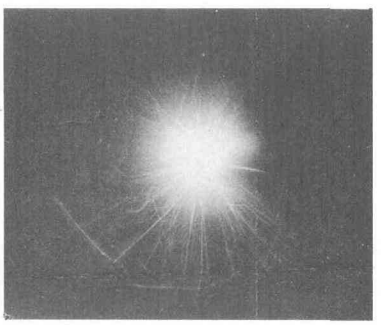
3



× 1

$S_2 = .200$ cm.

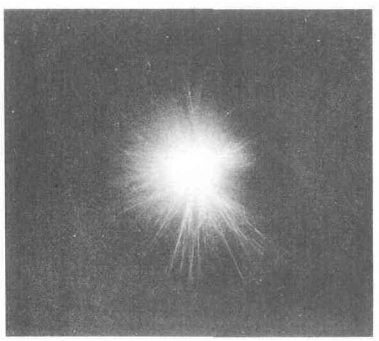
4



× 1

$S_2 = .350$ cm

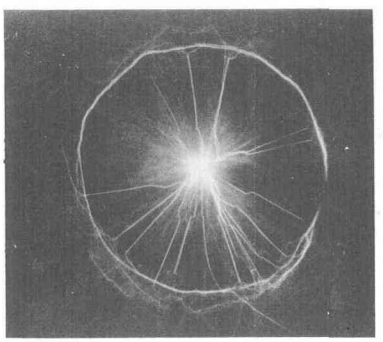
5



× 1

$S_2 = .500$ cm.

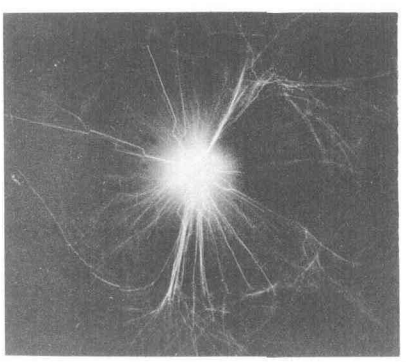
6



× 1

$S_2 = .700$ cm

7

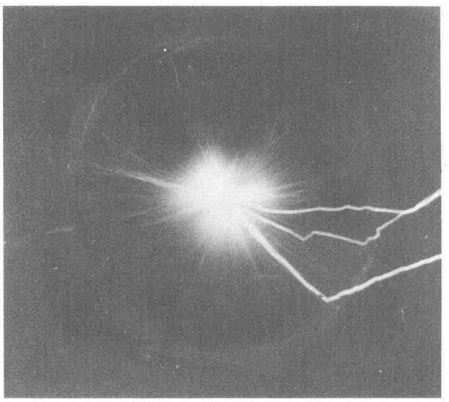


× 1

$S_2 = .90$ cm.

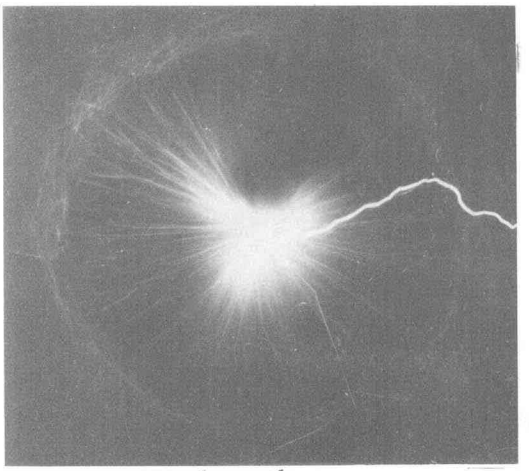
Fig. 10. Circular spark on the plate of sealing wax.

No. 11 ×1



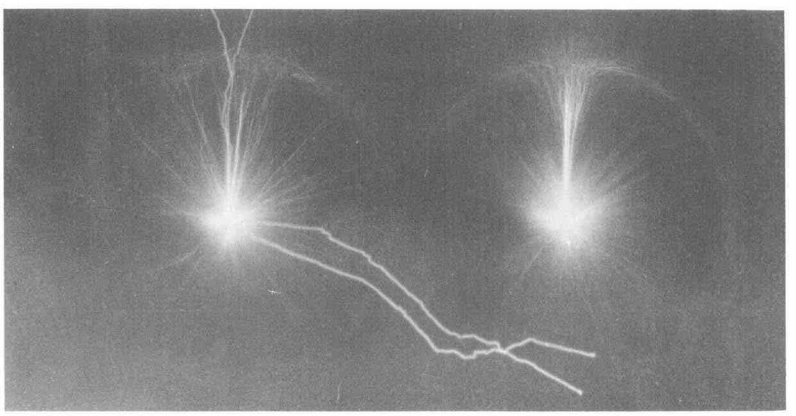
l=0.183 cm.

No. 16 ×1



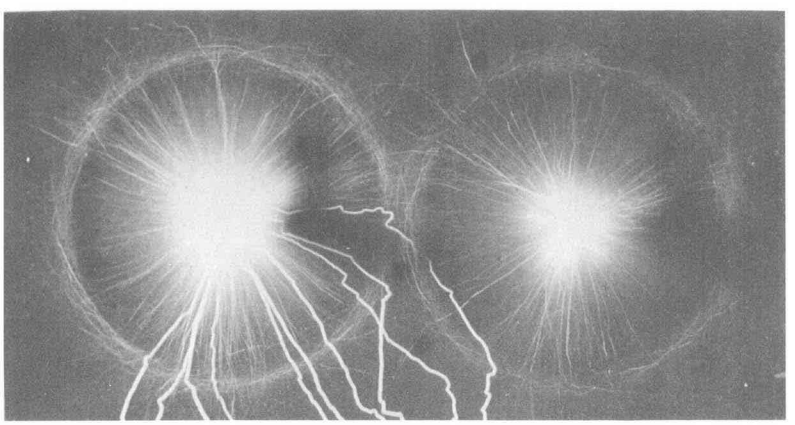
l=0.460 cm.

No. 12 ×1



l=0.185 cm.

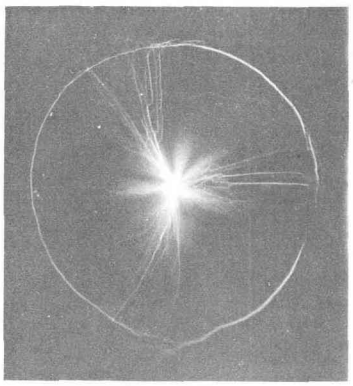
No. 13 ×1



l=0.213 cm.

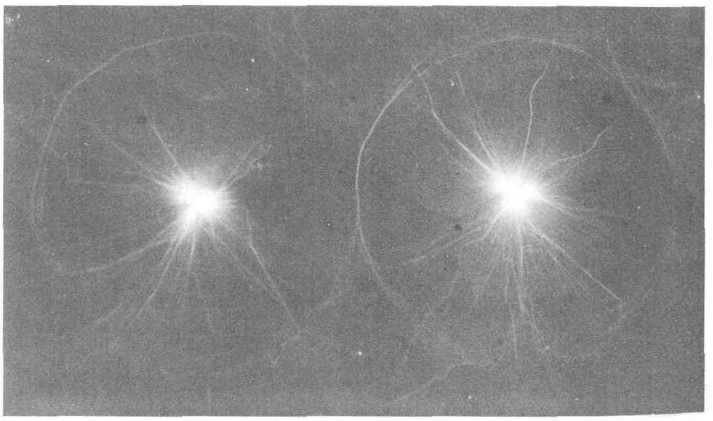
Fig. 12. Circular spark on plates of various substances.

× 1

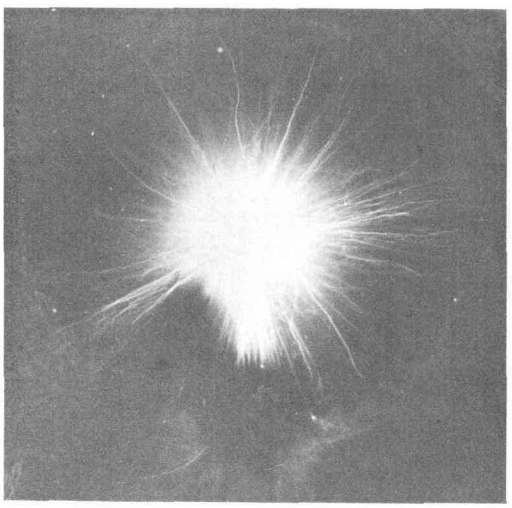


Glass : l=.285 cm.
(Transformer)

× 1

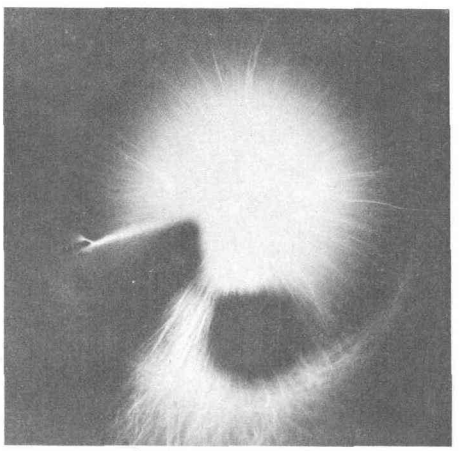


Glass : l=.35 cm. (Ind. coil)



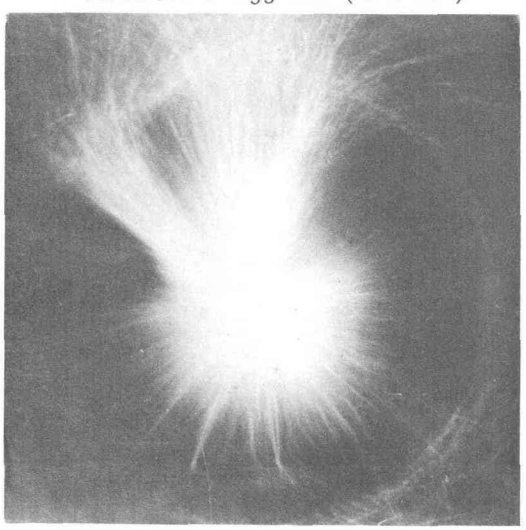
× 1

Ebonite : l=.33 cm. (Ind. coil)

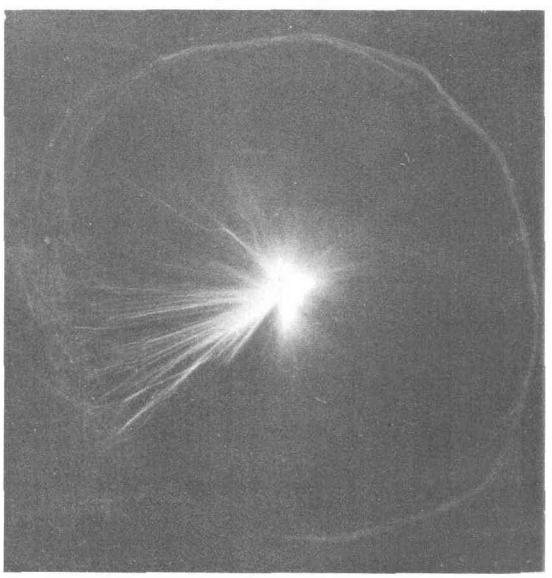


× 1

Bakelite : l=.315 cm.
(Ind. coil)



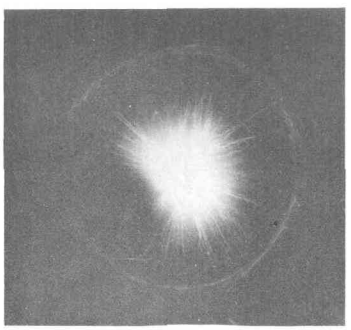
Porcelain : l=.60 cm. × 1
(Transformer)



Porcelain : l=.65 cm. × 1
(Transformer)

Fig. 13. Circular spark on different glass plates.

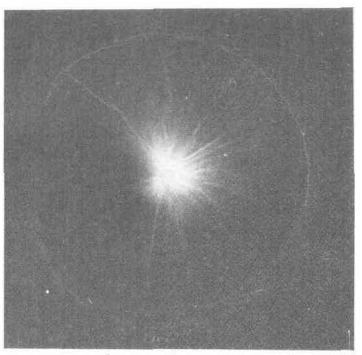
1



× 1

l=0.170 cm.

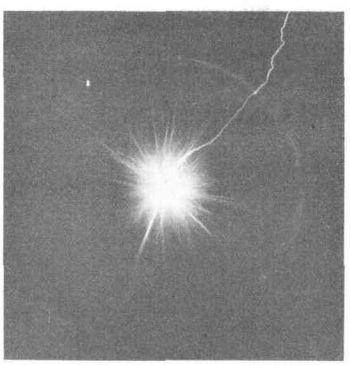
2



× 1

l=0.175 cm.

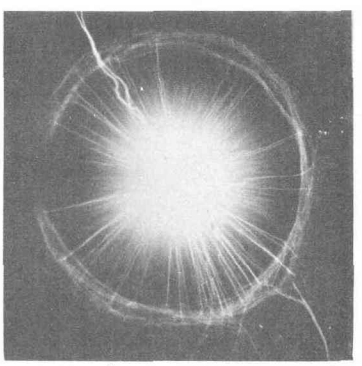
3



× 1

l=0.185 cm.

4



× 1

l=0.142 cm.