Coil L alone only with spark wires, no vertical wire:

Capacity total in primary circuit	Total primary self-induction turns of regulating coil+conn.	Height of ball from center to ground	Analyzing spark at s
$\frac{142}{2}=71$ bottles	9 7/8 turns+connections	*no ball, no wire*	3 3/4"

Coil *with* vertical wire and spark wires:

$\frac{142}{2}=71$ bottles	18 3/8 turns+connect.	*no ball*	3 1/4"

Coil with *ball, vertical wire* and spark wires:

$\frac{142}{2}=71$ bottles	19 1/2 turns+conn.	9 feet 5"	4"
,, ,,	20 3/8 ,, + ,,	33' 9"	4 3/8"
,, ,,	21 1/4 ,, + ,,	58' 9"	4 1/8"

Owing to the construction of the coil L which, as before stated, aimed at sharp tuning it was easy to detect a variation of $\frac{1}{16}$ of *one turn* of the regulating primary coil R.

It was desirable to take some readings with all the bottles in and the results were nearly the same and could still be read off with fair exactness, although the variation on the regulating coil R was reduced to one half, the capacity in the primary being just double that used in the experiments the results of which were just given.

The readings with all the condensers were as follows:

Capacity in primary total	Total self-induction in primary turns of reg. coil+connections	Height of ball from center to ground	Spark on terminals of L
286 bottles	10 1/8 + conn.	9' 5"	4 1/4"
,,	10 9/16+ ,,	33' 9"	4 1/2"
,,	11 + ,,	58' 9"	4 3/4"

Note to above experiments:

The vibration of the coil L with vertical wire and spark wires was found to be in resonance with the primary in another series of observations with

142 bottles 18 3/4 turns+connections

whereas before it was found to be so with 18 3/8 turns. When the different value 18 3/4 turns was observed the *wind* was *blowing hard* and it would seem as if this would have had the effect of increasing the apparent capacity of the aerial vertical conductor. This is to be followed up.

The experiments seemed to demonstrate clearly that the augmentation of the capacity as the ball was elevated was in a simple proportion to the height, for at the middle position the value found was very nearly the arithmetic mean of the values in the extreme positions.

Colorado Springs

Oct. 24, 1899

Tests continued on the effect of elevation upon the capacity of a body connected to earth.

The same coil was used as in the tests just before recorded, but the ball of 18" diam. was substituted for by one of 30" diam.

These readings were in all probability closer as an improvement in the procedure was made.

The results were as follows:

First set of readings.

Capacity in primary circuit Bottles total mfd.	Self-inductance of primary: Turns of reg. coil+ connections	Height of ball above ground from center	Analyzing spark on terminals of excited coil
$\frac{(8\times 36)-2}{2}=143=0.1287$	10 3/8+connections	9' 11"	4 1/2"
$\frac{(8\times 36)-2}{2}=143=0.1287$	10 3/4+ „	34' 3"	4 3/4"
$\frac{(8\times 36)-2}{2}=143=0.1287$	11 1/8+ „	58' 6"	5 1/8"

Second set of readings. Capacity reduced in primary to get greater variation on regul. coil.

$\frac{(4\times 36)-2}{2}=71=0.0639$	19 3/4+ „	9' 11"	4 3/8"

$\frac{(4 \times 36) - 2}{2} = 71 = 0.0639$	20 3/8+	,,	34' 3"	5 1/4"
$\frac{(4 \times 36) - 2}{2} = 71 = 0.0639$	21 +	,,	58' 6"	5 3/8"

Note: After these readings had been taken it was found that the ball sliding on the vertical wire did not make a good contact. This might have modified the results slightly.

Colorado Springs

Oct. 25, 1899

Experiments on influence of elevation upon capacity of conductor connected to earth continued:

This time simply a wire No. 10 extending vertically in the continuation of the axis of the coil was used. The coil was the same as before, 689 turns No. 20 cord on drum of 14" diameter. 36 feet of wire were first taken and after each reading 3 feet were cut off. Each time resonance with the primary was attained and the constants of the primary circuit noted, this giving the necessary data for the determination of the capacity of the vertical wire. The results are indicated below:

Capacity in the primary circuit total Bottles	mfd.	Self-inductance of primary Turns of reg. coil+connect.		Length of vertical wire in feet	Analyzing spark on terminals of excited coil
$\frac{(4 \times 36)}{2} = 71$	0.0639	17	+connect.	36	1/8"
,,	,,	16 3/8	+ ,,	33	,,
,,	,,	15 3/4	+ ,,	30	,,
,,	,,	15 1/4	+ ,,	27	1/16"
,,	,,	14 3/4	+ ,,	24	,,
,,	,,	14 1/4	+ ,,	21	,,
,,	,,	13 3/4	+ ,,	18	,,
,,	,,	13 1/4	+ ,,	15	,,
,,	,,	12 3/4	+ ,,	12	13/16"
,,	,,	12 1/4	+ ,,	9	9/16"

These readings are approximate.

Oct. 26, 1899

Measurement of inductance of 689 turn coil used in investigations on influence of elevation upon the capacity of a conductor.

Readings were as follows:

Volts av.	Current	ω	Res.
118	3.315	880	28.304

$$\frac{E}{I}=\frac{118}{3.315}=35.6 \qquad \left(\frac{E}{I}\right)^2=1267.36$$

$$R^2=800.89$$

$$\left(\frac{E}{I}\right)^2-R^2=466.47$$ *Large dynamometer close*

$$\omega^2=774,400$$

$$L^2=\frac{\left(\frac{E}{I}\right)^2-R^2}{\omega^2}=0.00057654$$ From this $L=0.024$ henry or $=$ **24,000,000** cm.

This is a value slightly smaller than that calculated before. Readings were also taken with small dynamometer. This slightly damaged. The readings are to be revised upon restandardizing.

Volts av.	Current av.	ω
69.25	2.045	880

$$\frac{E}{I}=33.863 \qquad \left(\frac{E}{I}\right)^2=1146.7 \qquad \left(\frac{E}{I}\right)^2-R^2=345.81$$

$$R^2=800.89$$

$$\omega^2=774,400$$

$$L^2=\frac{\left(\frac{E}{I}\right)^2-R^2}{\omega^2}=0.0004466$$ From this $L=0.0211$ henry or **21,100,000** cm.

Note: This value is decidedly too low owing to dynamometer indicating too large a current. Possibly during the test ω had changed.

Colorado Springs

Oct. 27, 1899

Test of condensers some of which were recently refilled. The corrections for capacity to be applied to the work of about two weeks ago.

Readings with 7 cells battery showed for *one half*

Microfarad Standard	Defl.	101, 101, 101	average 101°
For set of condensers all in multiple on left side from door		51, 51, 51	average 51°
For set of condensers all in multiple on right side from door		53, 53, 53	average 53°
For all condensers in multiple		104, 104, 104	average 104°

The difference between the two sets is probably due to different heights of solution in the tanks or bottles. In these measurements there were two bottles less on each side in the central tanks.

Taking the above data, the total number of bottles when all were in quantity was $(16\times 36)-4=576-4=572$ bottles.

The capacity was $\frac{104}{101}\times 0.5=$ **0.515 mfd** approx. This would give

for one bottle an average:	0.0009 mfd or	810 cm	These are frequently needed
„ two „ „	0.0018 „	1620 „	
„ three „ „	0.0027 „	2430 „	
„ 12 „ „	0.0108 „	9720 „	
for 36 bottles or one tank	0.0324 „	29,160 „	
„ 18 „ half of one tank	0.0162 „	14,580 „	

Note: Small mica condensers with fibre covers made for resonating circuits have a little less than 1/20 mfd each; two were measured.

Oct. 28, 1899

Referring to the preceding results the period of the excited system without the vertical wire was as follows:

Capacity in primary 71 bottles=0.0639 mfd.

Self-induction of primary connections plus 9 7/8 first turns of the regulating coil measured: 32,700 cm.

$$T_1=\frac{2\pi}{10^3}\sqrt{0.0639\times\frac{32{,}700}{10^9}}$$

With the vertical wire the period corresponding to that of the excited system was T_2, which estimated is:

Capacity in primary as before 0.0639 mfd.
Self-ind. in primary conn.+18 3/8 turns measured: 65,000 cm.

$$T_2=\frac{2\pi}{10^3}\sqrt{0.0639\times\frac{65{,}000}{10^9}}$$

Now calling C the capacity of the excited system with only the spark wires, L the self-induction of the excited coil, before found to be L=0.024 H, we have for the period of the excited system:

$$T_{s1}=\frac{2\pi}{10^3}\sqrt{0.024\times C},\quad C \text{ being in mfd. Now } T_{s1}=T_1 \text{ or}$$

$$0.024\times C=0.0639\times\frac{327}{10^7} \text{ and } C=\frac{327\times 0.0639}{10^7\times 0.024} \text{ mfd or}$$

$$C=\frac{9\times 10^5\times 327\times 0.0639}{10^7\times 0.024}=\frac{0.5771\times 327}{2.4}\text{ cm.}=\mathbf{78.36\ cm}=\mathrm{C}$$

Calling presently C_1, the capacity of the excited system when the vertical wire was attached, we have by similar reasoning from

$$T_{s2}=\frac{2\pi}{10^3}\sqrt{0.024\times C_1}=T_2=\frac{2\pi}{10^3}\sqrt{0.0639\times\frac{65{,}000}{10^9}}$$

$$C_1=\frac{65}{10^6}\times\frac{0.0639}{0.024}\text{ mfd, or } C_1=\frac{9\times 10^5\times 65}{10^6}\times\frac{0.0639}{0.024}\text{ cm}=\mathbf{155.76\ cm.}$$

The capacity of the wire alone would from these results be

$$C_1—C=155.76—78.36=\mathbf{77.40\ cm.}$$

Calculated approximately we have the following data for the wire: diam. of wire No. 10=0.2588 cm., r=0.1294 cm.

l=50 feet approx.=50×12×2.54=1524 cm.

16*

From this: $\frac{l}{r}=11{,}777.4$ and capacity of wire$=\frac{l}{2\log_e \frac{l}{r}}=\frac{1524}{18.7}=$ **81.5 cm.**

The calculated value is a little larger but not much, well within the errors of the adjustment and determination of the quantities by experiment.

Continuing we see that when the ball was at its lowest position the period of the primary was as follows:

Capacity in primary as before 0.0639
Inductance: connections+19 1/2 turns
measured 68,300 cm or $\frac{683}{10^7}$ H.

$$T_{pl}=\frac{2\pi}{10^3}\sqrt{0.0639\times\frac{683}{10^7}}$$

Similarly, when the ball was at its highest position, we have:

Capacity in primary circuit as before 0.0639
Inductance: connections+21 1/4 turns which, measured, were found: 76,100 cm, or $\frac{761}{10^7}$ H

$$T_{ph}=\frac{2\pi}{10^3}\sqrt{0.0639\times\frac{761}{10^7}}$$

Now calling C' the total capacity of the excited system when the ball was lowest, we have the period of the excited system:

$$T_{sl}=\frac{2\pi}{10^3}\sqrt{0.024\times C'}=\frac{2\pi}{10^3}\sqrt{0.0639\times\frac{683}{10^7}} \text{ from which } C'=\frac{0.0639\times 683}{0.024\times 10^7}\text{ mfd,}$$

$$\text{or } C' \text{ in cm}=\frac{9\times 10^5\times 0.0639\times 683}{0.024\times 10^7}=\mathbf{163.66\,cm}=\mathbf{C'}.$$

The ball at the lowest position effectively contributed only

$$C'\text{—}C_1=163.66\text{—}155.76=\mathbf{7.90\ cm}$$

but this low value was probably due to the fact that the vertical wire extended above.

Calculating similarly the value of C'', that is the capacity of the excited system when the ball was highest:

$$T_{sh}=\frac{2\pi}{10^3}\sqrt{0.024\times C''}\quad C''=\frac{0.0639\times 761}{10^7\times 0.024}=\text{in cm.}=182.36\text{ cm.}$$

Now $C''\text{—}C'=182.36\text{—}163.66=$ **18.70 cm** gives the actual value for the ball on top. This is an increase of nearly 137% for 49' 4" or about 2.76% per foot.

Experiments with coil 689 turns on drum 14" diam. were again continued to further study the influence of elevation upon capacity.

The same arrangement was used which was described on a previous occasion with vertical wire and ball 30" diam. The excitation of the coil was effected by connecting it to one of the terminals of the condensers, that which was joined to the terminal of the Westinghouse Transformer which was in connection with the tank — but the connection of the latter to the ground was not made directly but through a spark gap 1/8" long.

The spark wires leading to the spark gap, serving to observe resonant rise, were No. 26 guttapercha coated and each about 25 feet long: It was really only the upper wire leading from the free terminal which was of importance to consider. The vibration of the coil was first ascertained, nothing except the spark wires being attached. Next a sphere of 30" diam., the tin foil of which was cut through with a sharp knife to prevent formation of eddy currents, was connected to the top of the coil and the vibration again determined. Then the vertical wire was put on and the sphere taken off. After determining the vibration with the vertical wire the sphere was slipped on the same and readings taken with the sphere at different heights. The results were as follows:

Coil with spark wires alone.

Capacity in primary Bottles total mfd	Self-inductance of primary Turns of reg. coil+conn.	Analyzing spark on terminals of excited coil
$\frac{(4\times 36)-2}{2}=71=0.0639$	10 1/2+conn.	3"

Coil with ball of 30" diam. and spark wires.

Capacity in primary circuit Bottles total mfd	Self-inductance of primary. Turns in reg. coil+connections	Analyzing spark on terminals of excited coil
$\frac{(4\times 36)-2}{2}=71=0.0639$	13+conn.	3 1/2"

Coil with vertical wire No. 10, fifty feet and spark wires.

$\frac{(4\times 36)-2}{2}=71=0.0639$	19 3/4+conn.	3 7/8"

Readings with ball of 30" diam., vertical wire and spark wires connected to coil.

Capacity in primary circuit Bottles total mfd	Self-inductance of primary. Turns in reg. coil+conn.	Height of ball from center to ground	Analyzing spark on terminals of excited coil
$\frac{(4\times 36)-2}{2}=71=0.0639$	20 3/4+conn.	9' 11"	4 3/8"
$\frac{(4\times 36)-2}{2}=71=0.0639$	21 3/8+conn.	32' 8"	4 3/8"
$\frac{(4\times 36)-2}{2}=71=0.0639$	22 +conn.	55' 7"	4 3/8"

Readings continued with primary capacity modified.

$\frac{(8\times 36)-2}{2}=143=0.1287$	11 5/8+conn.	10' 3"	1/4"
$\frac{(8\times 36)-2}{2}=143=0.1287$	12 1/4+conn.	33' 3"	1"
$\frac{(8\times 36)-2}{2}=143=0.1287$	12 7/8+conn.	55' 9"	1 1/2"

The capacity in primary was now still further reduced.

The readings were as follows:

Capacity in primary Bottles total mfd	Inductance in primary. Turns in reg. coil+conn.	Height of ball above ground from center	Analyzing spark on terminals of excited coil
$\frac{(5\times 36)-2}{2}=89=0.0809$	16 1/2+conn.	10' 3"	4"
$\frac{(5\times 36)-2}{2}=89=0.0809$	17 3/8+conn.	33' 3"	4 1/4"
$\frac{(5\times 36)-2}{2}=89=0.0809$	18 1/4+conn.	55' 9"	4 3/8"

In these experiments the excitation of the coil was varied by adjusting the small spark gap separating one terminal of the Westinghouse transformer from the ground. The tuning was not very sharp as the ball was large and the magnifying factor of the coil rather small. Taking n approx. 60,000 we have $p=360{,}000$ approx., $R=28.3$, $L=0.024$ we have for $\frac{pL}{R}$ value $\frac{36\times 10^4\times 0.024}{28.3}=300$ approx. Not so small after all.

It was desirable to take some readings with the self-induction in the primary remaining the same, the capacity only being varied.

Following results were obtained:

Primary capacity Bottles total mfd	Primary self-induction. Turns in reg. coil.+conn.	Height of ball from center to ground	Analyzing spark on terminals of excited coil
$\frac{133}{2}=66.5=0.05985$	22+conn.	10′ 3″	4 3/8″
$\frac{137}{2}=68.5=0.06165$	22+conn.	33′ 3″	4 3/8″
$\frac{142}{2}=71\ \ =0.0639$	22+conn.	55′ 9″	4 3/8″

These data are to be worked out.

Colorado Springs

Oct. 30, 1899

Measurement of Inductances

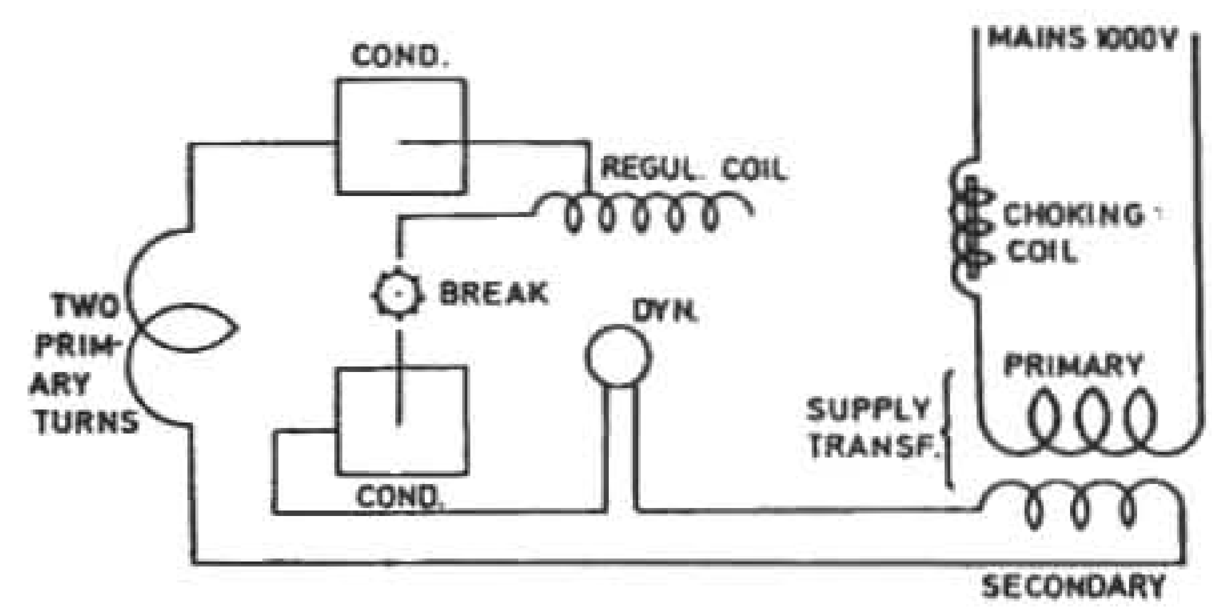
The primary of the oscillator, regulating coil and connections to spark gaps and condensers as generally used were joined in series, the gaps and condensers being bridged by short pieces of wire No. 2 of inappreciable resistance. The object was to determine again: the inductance of the primary turns of the oscillator, of the regulating coil for the various turns as employed and also of the connections. The two primary turns were joined in series and readings taken across both to get better values.

The generator, a 1500 light machine smooth armature Westinghouse type, was specially run, the speed being kept constant. The frequency was determined as before by taking the speed of synchronous motor running without any load and with strong excitation of field. There was no slip under these conditions as frequently ascertained.

The average speed was very closely 2070 per minute on a motor which was a 4-pole, this giving 8280 cycles per minute or 138 per second. From which $\omega=867$.

The connections as used are shown in diagram below:

The connections were all left exactly as used generally with the exception that, as before stated, the gaps and condensers were bridged by short pieces of wire No. 2.



Readings for: *two primary turns, regulating coil* 23.5 *turns* and *all connections in series:*

E	I	ω	R
14.7	53.00	867	
14.8	53.22	,,	
15.1	54.00	,,	
15.1	54.00	,,	

This gave an average of:

E	I	ω	R
14.925	**53.555**	**867**	

Readings for *two primary turns in series:*

E	I	ω	R
10.45	52.1	867	
10.35	52.1	,,	
10.40	52.1	,,	

This gave average values:

E	I	ω	R
10.4	**52.1**	**867**	

Readings were also taken across each one of the primary turns, the e.m.f. of course being exactly one half but the e.m.f. across the *upper* turn was *slightly greater*, probably because of the greater distance from the ground, possibly because of being nearer to the open secondary.

Readings for *regulating coil* 23.5 turns and *connections* of *break* and *condensers* together in series:

E	I	ω	R
4.1	52.1	867	
4.1	52.1	,,	
4.1	52.1	,,	

This gives average values:

E	I	ω	R
4.1	**52.1**	**867**	

Readings for *regulating coil alone* for *various turns:*

E	I	ω	Number of turns across which e.m.f. read	Resistance of the turns included
$\frac{7.85}{2}=3.925$	52.1	867	23.5	
$\frac{6.3}{2}=3.15$	52.1	867	19.5	
$\frac{4.8}{2}=2.4$	52.5	867	15.5	
$\frac{3.3}{2}=1.65$	53.00	867	11.5	
$\frac{2}{2}=1$	53.00	867	7.5	
0.5	53.00	867	3.5	

To get better readings for the separate turns of the regulating coil the voltage was taken again as first across the whole: 2 primary turns, connections and regulating coil all in series and the turns of the latter were then varied, readings being taken for each case. The results are indicated below:

E	I	Number of turns of the regul. coil included in the circuit	ω	Resistance total of circuit included
11.55	55.8	0.5	867	
11.675	55.8	2.5	"	
11.90	55.8	4.5	"	
12.15	55.3	6.5	"	
12.45	55.3	8.5	"	
12.80	55.3	10.5	"	
13.20	54.9	12.5	"	
13.50+a little	54.9	14.5	"	
13.90	54.9	16.5	"	
14.25	54.4	18.5	"	
14.60+a little	54.4	20.5	"	
14.15	51.1	22.5	"	
14.30	51.1	23.5	"	

To facilitate estimation of the inductance of the various turns the readings were reduced to the same value of current and are as follows:

11.55	55.8	0.5	867
11.675	55.8	2.5	"
11.90	55.8	4.5	"
12.26	55.8	6.5	"
12.562	55.8	8.5	"
12.915	55.8	10.5	"
13.416	55.8	12.5	"
13.721	55.8	14.5	"
14.128	55.8	16.5	"
14.617	55.8	18.5	"
14.976	55.8	20.5	"
15.452	55.8	22.5	"
15.616	55.8	23.5	"

Oct. 31, 1899

Measurement of inductances: New coil for further investigating effect of altitude upon capacity of body connected to earth.

The drum of 14" diam. and 8 feet long was again used, the cord No. 20 being taken off and wire No. 10 rubber- covered used instead. Most of the data from before remained, only the number of turns was reduced from 689 to 346.

The readings of e.m.f., current and frequency were as follows:

E	I	ω
85	15.635	880
84.75	15.6	,,
82.5	15.3	,,
	Average values:	
84.38	15.512	880

R	
coil with cord	1.752
cord	0.596
coil alone	1.156 ohm.

This gives: $\frac{E}{I}=5.44 \quad \left(\frac{E}{I}\right)^2=29.5936$ $\qquad R^2=1.3364$

$\omega^2=774,400$

$$L^2=\frac{\left(\frac{E}{I}\right)^2-R^2}{\omega^2}=\frac{29.5936-1.3364}{774,400}=\frac{28.2572}{774,400}\text{ henry}=0.00003649$$

$$\text{or } L=\sqrt{0.00003649}=\mathbf{0.00604\ H} \text{ or } \mathbf{L=6,040,000\ cm.}$$

Now for calculating with reference to note Oct. 18 we have the following data:

diam. of core 14"=35.5 cm

length of core 96"=243.84 cm=l
S=1000 sq. cm.
N=346
N^2=119,716

$$L=\frac{4\pi}{l}N^2S=\frac{12.5664\times 119,716,000}{243.84}$$

From this L=6,169,600 cm
or 0.00617 henry approx.
This is nearly 2% greater than measured value — fairly close.

Colorado Springs Notes

Nov. 1—30, 1899

Want of time compelled omission of following items partly worked out:

Nov. 27, 28 Corrected and completed results of experiments of

Nov. 3 $\left\{\begin{array}{l}\text{with wire of different}\\ \text{lengths and ball}\end{array}\right\}$, 19 and 21

Nov. 29, 30 $\left.\begin{array}{l}\text{a) Extra coils in series exciting one another,}\\ \text{b) Methods of tuning by telephone,}\\ \text{c) Exciting receiving circuit through small sensitive arc}\end{array}\right\}$ complete description

Patent matter worked on Nov. 1—30:

Exclusion of messages in telegraphy:

$\left.\begin{array}{l}\text{a) Two or more synchronized receiving circuits}\\ \quad\text{controlling receiver}\\ \text{b) Key or safety combination}\end{array}\right\}$ text to be completed.

Colorado Springs Nov. 1. 1899

Measurement of inductance of new extra coil built chiefly for investigating propagation of waves through the ground and similar objects. Also to investigate further the behaviour of strong streamers.

The frame was made of light notched woodwork fastened to three strong wooden rings. Provision was made for 106 turns. The rings were 8 feet in diam. and taking further 1½" on each side for the crosspieces the total diameter of coil inside was 8'3". The length was 8 feet less 1½" on top and ½" on bottom making total length of coil 7 feet 10". The data are as follows:

length of coil 7'10" = 94" = 238.76 C.m. = l ; diam. 8'3" = 99" = 251.46 C.m. = d

Turns made Nr. = 106 = N (really 105 more wound + one turn loose)

area $S = \frac{\pi d^2}{4} = 49662.52$ C.m. sq. From these data we have

$$L = \frac{4\pi}{l} N^2 S = \frac{12.5664 \times 11236 \times 49662.52}{238.76} = 208 \times 12.5664 \times 11236$$

$$= 141196 \times 208 =$$

$$L = \underline{29,368,768 \text{ C.m.}} \text{ or } \underline{0.029369 \text{ H.}} \text{ approx. } \underline{\text{calculated}}$$

Now the readings were.

E	J	ω	R
110	6.05	880	coil with cord 3.26
110	6.05	880	cord 0.596
110	6.05	880	coil alone 2.664

$\frac{E}{J} = 18.1818$ $\left(\frac{E}{J}\right)^2 = 330.58$

$R^2 = 7.097$

$\left(\frac{E}{J}\right)^2 - R^2 = 323.483$

$\omega^2 = 774400$

This gives $L^2 = \frac{323.483}{774400} = 0.000417721$

$$L = \sqrt{0.000417721} = \underline{0.02042 \text{ H}} \sim \underline{20,420,000} \text{ C.m.}$$

Measurement shows a value much lower but this was to be expected as the turns are large also few spaced ½". However the measurement is to be made again to be sure of the values.

Nov. 1, 1899

Measurement of inductance of new extra coil built chiefly for investigating propagation of waves through the ground and similar objects. Also to investigate further the behaviour of strong streamers.

The frame was made of light notched woodwork fastened to three strong wooden rings. Provision was made for 106 turns. The rings were 8 feet in diam. and taking further 1 1/2" on each side for the crosspieces the total diameter of coil inside was 8'3". The length was 8 feet less 1 1/2" on top and 1/2" on bottom making total length of coil 7 feet 10". The data are as follows:

Length of coil 7' 10"=94"=238.76 cm=l; diam 8' 3"=99"=251.46 cm=d

Turns wire No.10 106=N (really 105 turns wound+one turn loose)

Area $S=\frac{\pi d^2}{4}$=49,662.52 cm.sq. from these data we have

$$L=\frac{4\pi}{l}N^2 S=\frac{12.5664\times 11{,}236\times 49{,}662.52}{238.76}=208\times 12.5664\times 11{,}236$$

$$=141{,}196\times 208$$

L=**29,368,768 cm,** or **0.029369 H** approx.

Now the readings were: *Calculated*

E	I	ω	R	
110	6.05	880	Coil with cord 3.26	
110	6.05	880	cord 0.596	
110	6.05	880	Coil alone 2.664	

$$\left(\frac{E}{I}\right)=18.1818 \quad \left(\frac{E}{I}\right)^2=330.58$$
$$R^2=7.097$$
$$\left(\frac{E}{I}\right)^2-R^2=323.483$$
$$\omega^2=774{,}400$$

This gives $L^2=\frac{323.483}{774{,}400}$=0.000417721

$L=\sqrt{0.000417721}$=**0.02042 H** or **20,420,000 cm.**

Measurement shows a value much lower but this was to be expected as the turns are large also 1/2" apart. However this measurement is to be made again to be sure of the result.

Nov. 2, 1899

Readings were again taken today to ascertain the value found yesterday for inductance of new extra coil. The results were as follows:

E	I	ω	R	
194	10.7	887	2.664	average of three readings very closely agreeing.

$$\left(\frac{E}{I}\right)=18.13 \qquad \left(\frac{E}{I}\right)^2=328.6969$$

$$R^2=\quad 7.0969$$

$$\left(\frac{E}{I}\right)^2-R^2=321.60$$

$$L=\frac{\sqrt{321.6}}{887}=\frac{17.933}{887}$$

L=**0.0202176** henry or **20,217,600 cm.**

This is a value a little smaller than the one found yesterday but it is within the limits of variation of ω.

Note: When the turns are far apart the ordinary formulas for calculating do not apply, and the measured value is the more inferior to the calculated value the greater the turns and the farther apart they are. When very far apart it is better to calculate inductance of one turn and multiply or, if they are not all alike, to calculate then separately and add up, making some allowance for mutual induction.

Secondary last form, two wires No. 10 in multiple 17 turns on frame described on another occasion. To test the values before found for inductance and mutual induction coefficient readings were again taken today. For secondary inductance:

E	I	ω	R	
138	16.5	887	1.382	The first two readings were in all probability the best and they are taken.
138	16.5			
136	16.3	875		
134.5	16.2			

From above:

$$\frac{E}{I}=8.364 \quad \left.\begin{array}{c}\left(\frac{E}{I}\right)^2=69.9565 \\ R^2=1.91\end{array}\right\} \quad \begin{array}{c}\left(\frac{E}{I}\right)^2-R^2=68.0465 \\ \omega=887\end{array}$$

$$L=\frac{\sqrt{64.0465}}{887}=\frac{8.003}{887}=\mathbf{0.009023\ H\ or\ 9{,}023{,}000\ cm.}$$

This is smaller than before found because the turn before last was wound a little higher up as at first sparks would break through. It is to be measured once more however.

Readings for *Mutual Induction* Coefficient.

Two primary turns in series:

Current through primary two turns in series	Volts on secondary	
I	E	ω
45.4	34	880
45.4	34	,,
45.4	34	,,

From this $E=M\omega I$, $M=\frac{34\times 10^9}{880\times 45.4}=$ **851,021 cm.**

Readings with current through the secondary gave:

Current through secondary	Volts on primary two turns series	ω
17.8	13.4	872 } over
17.8	13.4	,,

From later readings $M=\frac{13.4\times 10^9}{17.8\times 872}=$ **863,313 cm.**

This is a little larger probably due to variation of ω. Readings were now taken for each of the primary turns separate with the following results:

Upper primary turn, nearer to secondary:

Current through secondary	E.m.f. on primary	ω
17.9	6.9	872 average three readings

From this $M_{\text{upper pr.}}=\frac{6.9\times 10^9}{17.9\times 872}=$ **442,059 cm.**

Current through primary	E.m.f. on secondary	ω
30.1	11.8	880 average three readings

$$M_{\text{upper. pr.}}=\frac{11.8\times 10^9}{30.1\times 880}=\mathbf{445{,}484\ cm.}$$

The difference again in all probability to be ascribed to variation of ω.

Lower primary turn. Readings were as follows:

Current through primary	E.m.f. secondary	ω
30.1	11.1	880 average three readings
Current through secondary	E.m.f. primary	
17.9	6.4	880 average three readings

From first set readings: From second set readings:

$$M_{\text{lower pr.}} = \frac{11.1 \times 10^9}{30.1 \times 880} = \mathbf{419{,}060\ cm.} \qquad M_{\text{pr. lower}} = \frac{6.4}{17.9 \times 880} = \mathbf{406{,}300\ cm.}$$

For two primary turns multiple

Current through primaries	E.m.f. secondary	ω
29.2	11.25	880 average three readings
Current through secondary	E.m.f. primaries	
17.9	6.7	880 average three readings

From first set of readings: From latter readings:

$M_{2\ \text{prim. multiple}} = \mathbf{437{,}811\ cm}$ $M_{2\ \text{pr. multiple}} = \mathbf{425{,}343\ cm}$

Colorado Springs

Nov. 3, 1899

Investigation for the purpose of ascertaining the influence of elevation upon the capacity of a conductor connected to a vibrating system as before used, continued:

The coil of 346 turns, No. 10 wire wound on drum 14" diam., 8 feet long was again used. The spark wires were as before No. 26 guttapercha covered, 24 feet long each. The readings were as follows:

Capacity in primary circuit *total*	Inductance in primary turns reg. coil+conn.	Length of vertical wire attached to free terminal of excited coil	Analyzing spark on terminals of excited coil
$\frac{(3 \times 36) - 2}{2}$ =53 bottles= =0.0479 mfd	7 1/8+conn.	45 feet	3 3/8"
0.0479 mfd	6 3/8+ „	36 „	3 3/8"
„	5 3/4+ „	27 „	3 3/8"
„	5 3/16+ „	18 „	3 1/4"
„	4 3/8+ „	9 „	3 1/8"
„	3 5/8+ „	0 „	3 1/8"

Note: As repeatedly observed, the first addition of a small length of wire to a coil generally produces a great effect but a certain small length being bypassed the increase per unit of length becomes more gradual.

Experiments with coil 346 turns on drum 14" diam. with the view of investigating influence of elevation upon the capacity of a body connected to earth continued. This time in connection with the vertical wire a ball 30" diam. was used in the manner before described.

Coil with spark wires alone

Capacity in primary circuit *total*	Turns in regulating coil+connections } Inductance	Analyzing spark on terminals of excited coil
$\frac{(3\times 36)-2}{2}$=53 bottles= =0.0479 mfd	3 5/8 +conn.	3 1/8"
Coil with 50 feet wire No. 10 vertical		
0.0479 mfd	7 3/4+conn.	4"
Coil with ball 30" diam. lowest position 10'3" from center to ground		
0.0479 mfd	8 1/2+conn.	4 1/8"
Coil with ball mean position 33'9" from center to ground		
0.0479 mfd	8 7/8+conn.	4 1/4"
Coil with ball highest position 57'3" from center to ground		
0.0479 mfd	9 1/4+conn.	4 3/8"

Note: The excitation in this and previous case was as before described by connecting the lower terminal of coil to that terminal of the condensers (primary) which was connected to small adjustable spark gap, specially made for this purpose, to earth.

It would be desirable in these tests to do away with the spark wires as these are apt to introduce errors in the estimates of capacity. Experiments were made with new extra coil to see how close the maximum rise could be ascertained without any spark wires, merely by observing the streamers. For this purpose the extra coil was excited from the secondary of oscillator as in some previous instances. First the extra coil was tuned with spark wires, then the upper wire which is the only one of importance was taken off and the system again tuned. The results were as follows:

New Extra coil with Spark wires Guttapercha No. 26, 24 feet long

Capacity in primary circuit total (bottles / mfd)	Inductance in primary circuit Turns of regul. coil+connections
$\frac{(8\times 36)-2}{2}$=143 bottles=0.1287	7 5/8+connections

New Extra coil without upper Spark wire

$$\frac{(8 \times 36) - 2}{2} = 143 \text{ bottles} = 0.1287 \qquad 5\ 5/8 + \text{connections}$$

Colorado Springs

Nov. 4, 1899

Measurement of inductance of primaries.

Another series of readings were taken with the object of closely determining the inductance of the primary turns. This time a different dynamo was supplying the current. The speed was kept very constant. The readings were as follows:

Current	Electromotive force across two primaries in series	ω
345°=58.8	12 a trifle less	880
345°=58.8	12 ,,	,,
345°=58.8	12 ,,	,,

Allowing a little for zero displacement on voltmeter the average is very closely:

I	E	ω	R two primary turns in series
58.8	11.95	880	0.004 ohm.

This gives $\frac{E}{I}=0.2032 \qquad \left(\frac{E}{I}\right)^2=0.04129 \qquad R^2=0.000016$

Since R^2 is entirely negligible against $\left(\frac{E}{I}\right)^2$ we have:

$$L=\frac{E}{I\omega}=\frac{11.95}{51{,}744}=0.000230945 \text{ henry}$$

or **230,945 cm.**

This would give for one primary turn approximately

0.000057736 henry or **57,736 cm.**

The value previously found was 56,400 cm.
Reading of today would appear more reliable.

Capacity of structure of iron pipes, before described, computed:

7" pipe: Outside diam. 7.625"=19,3673 cm=d

length of pipe with cap=l=23' 4"=280"=811.2 cm=l

$$C_1=\frac{l}{2\log_e\frac{l}{r}}=\frac{811.2}{2\times4.42313}\qquad r=9.6837\quad \frac{l}{r}=83.77$$

$$\mathbf{C_1=91.7\ cm.}\qquad \log_e\frac{l}{r}=1.9231\times2.3=4.42313$$

6" pipe: Outside diam.=6.625"=16.8275 cm=d

length of pipe 18' 2"=218"=553.72 cm=l

$$C_2=\frac{l}{2\log_e\frac{l}{r}}=\frac{553.72}{2\times4.182}\qquad r=8.4138\quad \frac{l}{r}=65.81$$

$$\mathbf{C_2=66.2\ cm.}\qquad \log_e\frac{l}{r}=1.818292\times2.3=4.182$$

5" pipe: Outside diam. 5.563"=14.13 cm=d

length of pipe 18' 4 1/2"=220.5"=560.07 cm=l

$$C_3=\frac{l}{2\log_e\frac{l}{r}}=\frac{560.07}{2\times4.368}\qquad r=7.065\quad \frac{l}{r}=79.27$$

$$\mathbf{C_3=64.11\ cm.}\qquad \log_e\frac{l}{r}=1.89911\times2.3=4.368$$

4" pipe: Outside diam. 4.5"=11.43 cm=d

length of pipe 15' 7 1/4"=187.25"=475.615 cm.=l

$$C_4=\frac{l}{2\log_e\frac{l}{r}}=\frac{475.615}{8.832}\qquad r=5.715\quad \frac{l}{r}=83.22$$

$$\mathbf{C_4=53.85\ cm.}\qquad \log_e\frac{l}{r}=1.92\times2.3=4.416$$

3 1/2" pipe: Outside diam. 4"=10.16 cm=d

length of pipe 19' 3 1/4"=231.25"=587.375 cm=l

$$C_5=\frac{l}{2\log_e\frac{l}{r}}=\frac{587.375}{9.49} \qquad r=5.08 \qquad \frac{l}{r}=115.6$$

$$C_5=\mathbf{61.9\ cm.} \qquad \log_e\frac{l}{r}=2.062958\times 2.3=4.745$$

3" pipe: Outside diam. 3.5"=8.89 cm=d

length of pipe 18' 4 3/4"=220.75"=560.7 cm=l

$$C_6=\frac{l}{2\log_e\frac{l}{r}}=\frac{560.7}{2\times 4.83} \qquad r=4.445 \qquad \frac{l}{r}=126.1$$

$$C_6=\mathbf{58.05\ cm.} \qquad \log_e\frac{l}{r}=2.1\times 2.3=4.83$$

2 1/2" pipe: Outside diam. 2.875"=7.3 cm=d

$$\left.\begin{array}{l}\text{length of pipe } 8'\ 1/4'' \\ \quad ,,\quad \text{nipples } 7\ 3/4''\end{array}\right\}\ 8'\,8''=104''=264.16\ \text{cm}=l$$

$$C_7=\frac{l}{2\log_e\frac{l}{r}}=\frac{264.16}{2\times 4.276} \qquad r=3.65 \qquad \frac{l}{r}=72.37$$

$$C_7=\mathbf{30.89\ cm.} \qquad \log_e\frac{l}{r}=1.859\times 2.3=4.276$$

from above we have *total capacity* of structure

C:	7" pipe with cap	91.7 cm.
	6" pipe	66.2 ,,
	5" pipe	64.11 ,,
	4" pipe	53.85 ,,
	3 1/2" pipe	61.9 ,,
	3" pipe	58.05 ,,
	2 1/2" pipe	30.89 ,,
	Ball 30" diam.	38.1 ,,
	Total Capccity	C=464.8 cm.

Note: This supposes of course that all these capacities are connected in multiple. To be true it must be assumed that only long waves are used. With short waves the calculated value would not be experimentally borne out.

Colorado Springs

Nov. 6, 1899

Determination of el. st. *capacity* of the structure of iron pipes *by measurement.*

The method previously employed for such a purpose was again used. The coil described on a former occasion, wound on a drum of 10 5/16" and having 550 turns was excited from a vibrating primary system and the maximum resonant rise obtained with only the spark wires attached to the terminals of the coil. Then the upper terminal of the latter was connected to the structure and the maximum rise again obtained. From the two known periods of the primary system and the self-induction of the coil the capacity of the structure was then computed. In order to avoid errors due to the capacity of the wires connected to the coil the precaution was taken to make no change which would in any considerable way affect the result. Thus, when the vibration of the coil with only the spark wires was determined the wire which was to be later connected to the structure was likewise fastened to the upper terminal of the coil in a position such that in the second experiment or series of experiments it was only necessary to tilt the wire to bring it in contact with the structure. If this precaution would not be observed the error introduced by the connecting wire might be — and in fact it would generally be — considerable. The adjustments were first made with the spark wires and the wire which was to be connected to the structure, this wire being placed vertically and at a distance of about four feet from the latter. The maximum rise was observed on the terminals of the excited coil with:

Capacity in primary circuit total	Turns in regulating coil	Spark analyzing on terminals
$\frac{(8\times 36)-2}{2}$=143 Bottles or 0.1287 mfd	2 1/8	2 5/8"

Now the wire was tilted and brought in contact with the structure and resonant maximum rise was observed with:

$\frac{(8\times 36)-2}{2}$=143 Bottles=0.1287 mfd	17 1/2	2 5/8"

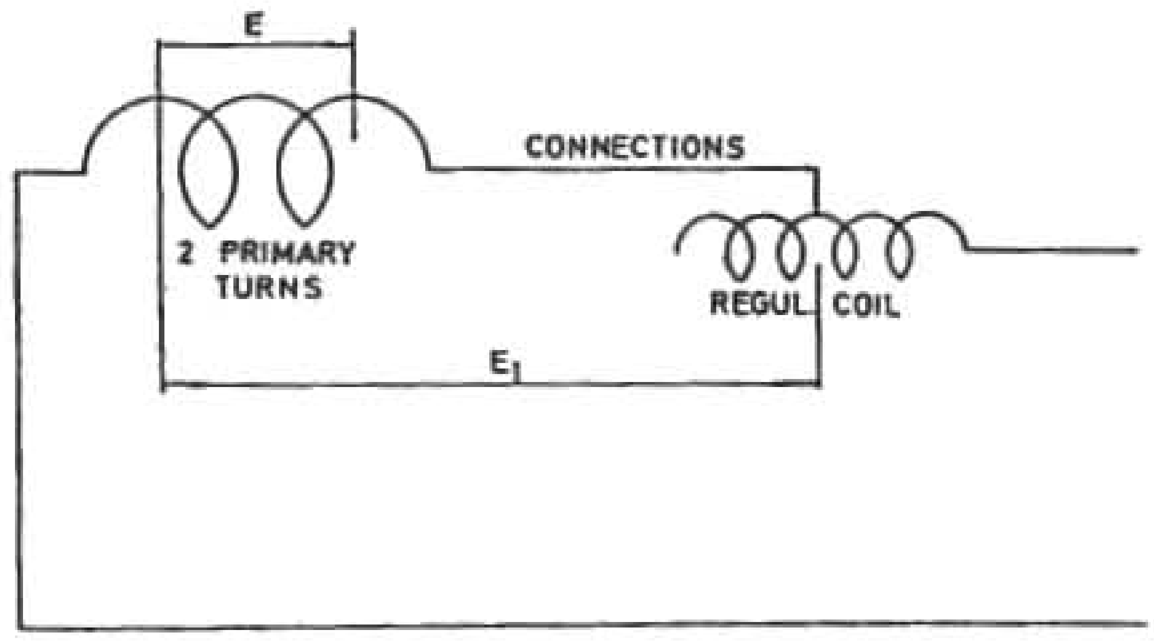
To determine more satisfactorily the self-induction in both the primary vibrations readings were taken in the following manner. The two primary turns, connections to breaks and condensers and the regulating coil were all connected in series — the breaks and condensers being of course bridged by stout and short wires (No. 2 being used) and readings of e.m.f. across the two primary turns were first taken and then across the two primaries plus connections and turns in the regulating coil as were used in the two instances. Since the resistances were entirely negligible with respect to the inductances it was only necessary to make the ratio of the e.m.f. in two instances to determine the inductance of the connections and turns from the known inductance of the two primary turns which was carefully determined before. As the readings were taken practically at the same moments across the primaries alone and across the primaries connections and turns ω could not vary perceptibly, and to make sure of that the readings were taken repeatedly. The current passed through the inductances also remaining the same during the two consecutive readings, the results ought to be therefore more reliable then those obtained otherwise.

The results in the first case were as follows:

$$\left.\begin{array}{l} E_1 = 10.4 \text{ volts} \\ E = 10 \quad \text{volts} \end{array}\right\} \quad \begin{array}{l} I \text{ and } \omega \\ \text{the same.} \end{array}$$

In the second case:

$$\left.\begin{array}{l} E_1 = 13.15 \text{ volts} \\ E = 10.3 \quad \text{,,} \end{array}\right\} \quad \begin{array}{l} I \text{ and } \omega \\ \text{the same.} \end{array}$$



Calling now L the inductance of the two primary turns in series and L_1 that of the two primaries+connections+2 1/8 turns of the regulating coil we have in first case:

$$\frac{E_1}{E} = \frac{L_1}{L} \text{ and } L_1 = \frac{E_1}{E} L$$

Now L was previously determined to be 230,945 cm, hence

$$L_1 = \frac{104}{100} \times 230{,}945 = 240{,}183 \text{ cm.}$$

From this inductance of the connections+2 1/8 turns of the regulating coil is $L_1 - L =$ $=9238$ cm.

In the second case we have similarly

$$L_2 = \frac{13.15}{10.3} \times 230{,}945 = 294{,}847 \text{ cm.}$$

L_2 being inductance of two primaries+connections+17 1/2 turns of regulating coil.

Hence the inductance of the connections and the turns (17 1/2) included is $L_2 - L =$ $=63{,}902$ cm.

From these data the capacity of the structure can now be estimated as follows: In the first case the primary vibration was

$$T = \frac{2\pi}{10^3} \sqrt{\frac{9238}{10^9} \times 0.1287}$$

In the second case the primary vibration was

$$T_2 = \frac{2\pi}{10^3} \sqrt{\frac{63{,}902}{10^9} \times 0.1287}$$

Calling now C_s the capacity of the excited system when the structure was not attached to it, and C_s' that when this was the case we have:

$$T_1 = \frac{2\pi}{10^3}\sqrt{C_s L'} = \frac{2\pi}{10^3}\sqrt{\frac{9238}{10^9} \times 0.1287}$$

and

$$T_2 = \frac{2\pi}{10^3}\sqrt{C_s' L'} = \frac{2\pi}{10^3}\sqrt{\frac{63,902}{10^9} \times 0.1287}$$

L' being the inductance of the excited coil. L' was previously measured and found to be $L' = 18,650,000$ cm. Now from above:

$$C_s = \frac{9238 \times 0.1287}{10^9 \times \frac{18,650,000}{10^9}} = \frac{9238 \times 0.1287}{18,650,000};$$

and

$$C_s' = \frac{63,902 \times 0.1287}{18,650,000}; \quad \frac{C_s'}{C_s} = \frac{63,902}{9238}; \quad C_s' = C_s \frac{63,902}{9238}$$

C_s expressed in centimeters is:

$$C_s = \frac{9238 \times 0.1287 \times 9 \times 10^5}{1865 \times 10^4} = \frac{11.583 \times 9238}{1865} = 57.375$$

from this $C_s' = \frac{63902}{9238} \times 57.375 = 6.92 \times 57.375 = 397.03$ **cm.**

$C = C_s' - C_s = 339.655$ **cm.**

This is a result inferior to the calculated value but it was to be expected as before stated since it can not be correct to assume that all pipes are connected in multiple unless the vibration is very slow. Another coil is to be used with an inductance much higher so as to examine the truth of this opinion. There is, however, a possibility that the reading, when the structure was attached to the excited coil, was too low. In this case namely, the tuning is *not sharp* owing to the large capacity of the system but when the structure is *not* attached it is quite sharp, hence if there is any error in the adjustment of the circuits it can be only then when the structure was connected. This is to be investigated also. A slight error might have been also caused by the wire which connected the coil to the structure, for although this wire was placed at a distance of 4 feet with its nearest point there might have been enough influence exerted by the structure to make the reading with the spark wires alone larger. This will be ascertained. From previous tests on the increase of capacity with elevation I should expect to find the capacity of the structure much larger than the calculated value.

On the present occasion readings were also taken with the view of determinig the inductance of the connections alone+flexible cable on regulating coil+1/2 turn of regulating coil. This namely is the lowest value which it is possible to give with the regulating coil in circuit. In this case the readings were $E_1 = 10.5$, $E = 10.2$ across the 2 primaries+ +all these connections and across the two primaries alone, respectively. With reference to foregoing and calling L_3 the inductance of the two primaries+connections+flexible cable+1/2 turn of regulating coil:

$$L_3 = \frac{105}{102} \times L = \frac{105}{103} \times 230{,}945 = 237{,}738 \text{ cm.}$$

Hence the inductance of all these mentioned connections is L_3—L=237,738—230,945=

$$= 6793 \text{ cm, for} \begin{cases} \text{connections proper} \\ \text{1/2 turn regulating coil,} \\ \text{flexible cable in reg. coil.} \end{cases}$$

Note: A small error is often caused by the changing position of the flexible cable which makes the readings for a small number of turns *larger* (slightly).

Colorado Springs

Nov. 7. 1899

Further experiments for the purpose of ascertaining the capacity of the structure of the iron pipe by resonance analysis. Two sets of readings were taken: one set with new extra coil the other with coil 346 turns wire No.10 on drum 14" diam. The readings were as follows:

With new extra coil

Capacity in primary exciting circuit *total:*	Inductance in primary circuit. Turns of regulating coil+conn.	Analyzing spark on *terminals of* excited coil.
$\frac{(8\times 36)-2}{2}$=143 bottles=0.1287 mfd	22+conn.	2 5/16"
$\frac{(8\times 36)-2}{2}$= ,, =0.1287 mfd	8+ ,,	3 3/4"

With experimental coil described

$\frac{(3\times 36)-2}{2}$= 53 bottles=0.0477 mfd	15.75+conn.	4"
$\frac{(3\times 36)-2}{2}$= ,, =0.0477 mfd	3.5+ ,,	3 1/8"

*Note: The first readings are of course *with*, the second *without* structure in each case.

*Note: Readings were also taken on this occasion with coil wound on 10 5/16" drum before described (550 turns) but merely for the purpose of comparing the inductances of the primary and secondary circuits. With the same capacity as in the last case resonance was obtained with spark wires alone:

$\frac{(3 \times 36) - 2}{2} = 35$ bottles $= 0.0477$ mfd 8 7/8 3 1/4"

This for *future reference.*

Returning to the two sets of observations it is to be noted that *one* turn of the new extra coil had been taken off and allowance should be made for this.

Let the primary vibration in the first case be T_{p_1} and the corresponding secondary vibration T_{s1} then $T_{p1} = T_{s1}$. Similarly for the second reading with the extra coil when the structure was not attached to the coil. Calling the respective vibration T_{p2} and T_{s2} we have $T_{p2} = T_{s2}$. Now

$$T_{p1} = \frac{2\pi}{10^3}\sqrt{L_{p1} \times C} \text{ and } T_{p2} = \frac{2\pi}{10^3}\sqrt{L_{p2} \times C}$$

where L_{p1} and L_{p2} designate the inductances of the primary circuit in the two cases. From this

$$\frac{T_{p1}}{T_{p2}} = \sqrt{\frac{L_{p1}}{L_{p2}}}$$

as useful relation to remember.

While the self-induction was varied in the primary circuit, and the capacity remained the same, in the secondary it was just the opposite, the self-induction remaining the same and the capacity being varied. Calling now the capacity of the excited system with the structure C_{s1} and without the structure C_{s2} (that of coil with spark wires alone) we have by analogous reasoning:

$$\frac{T_{s1}}{T_{s2}} = \sqrt{\frac{C_{s1}}{C_{s2}}} = \frac{T_{p1}}{T_{p2}} = \sqrt{\frac{L_{p1}}{L_{p2}}} \text{ or } \frac{C_{s1}}{C_{s2}} = \frac{L_{p1}}{L_{p2}}.$$

This is also a convenient equation and useful to bear in mind. In cases when the capacity in the excited system is very often varied it is only necessary to determine the first capacity with which the series of experiments was begun to know all the other values from the known inductances of the primary circuit in two consecutive experiments. But when there are only two values to be determined, as in the present instance, they can be at once calculated from the known primary vibrations.

In the present instance, adopting this procedure we have:

$$T_{p1} = \frac{2\pi}{10^3}\sqrt{0.1287 \times 0.000079} \quad \text{and } L_{p1} \begin{cases} \text{Connections } +22 \text{ turns:} \\ = 79{,}000 \text{ cm.} = 0.000079 \text{ H} \end{cases}$$

$$T_{p2} = \frac{2\pi}{10^3}\sqrt{0.1287 \times 0.00002526} \quad L_{p2} \begin{cases} \text{Connections } +8 \text{ turns reg. coil} \\ = 25{,}260 \text{ cm.} = 0.00002526 \text{ H} \end{cases}$$

$$T_{p1} = T_{s1} = \frac{2\pi}{10^3}\sqrt{C_{s1} \times 0.02}$$

$$T_{p2} = T_{s2} = \frac{2\pi}{10^3}\sqrt{C_{s2} \times 0.02}$$

Inductance of extra coil before measured was 0.02042 henry. This owing to one turn less without *change of length* should be reduced to ratio $\left(\frac{105}{106}\right)^2$ or about 2% making the inductance very approx. 20,000,000 cm. or 0.02 henry.

From the above:

$$\frac{2\pi}{10^3}\sqrt{C_{s1} \times 0.02} = \frac{2\pi}{10^3}\sqrt{0.1287 \times 0.000079}$$

and

$$C_{s1} = \frac{0.1287 \times 0.000079}{0.02} \text{ mfd,}$$

or in centimeters:

$$C_{s1} = \frac{9 \times 10^5 \times 0.1287 \times 0.000079}{0.02} = \mathbf{457.5} \text{ cm.}$$

Similarly we have

$$C_{s2} = \frac{0.1287 \times 0.00002526}{0.02} \text{ mfd, or}$$

$$C_{s2} = \frac{9 \times 10^5 \times 0.1287 \times 0.00002526}{0.02} = \mathbf{146.29} \text{ cm.}$$

This would give for the capacity of the structure according to this method only $C_{s1} - C_{s2} = 457.5 - 146.29 = \mathbf{311.21}$ **cm.**

This inferior result I attribute to the fact that the capacity is partially to be taken as *distributed*, owing to the length of the structure. But determining by the same method with a vibration which would be much slower this error should be very small.

Taking now the values for the set of readings with the experimental coil of 346 turns we have:

$$T'_{p1} = \frac{2\pi}{10^3}\sqrt{0.0377 \times 0.00005486} \text{ and } L_{p1} = \text{connections} + 15.75 \text{ turns}$$
$$= 54{,}860 \text{ cm.} = 0.00005486 \text{ H}$$

$$T'_{p2} = \frac{2\pi}{10^3}\sqrt{0.0377 \times 0.00001116} \qquad L_{p2} = \text{conn.} + 3\ 1/2 \text{ turns} =$$
$$= 11{,}160 \text{ cm.} = 0.00001116 \text{ H}$$

The inductance of the experimental coil measured being 6,040,000 cm, or 0.00604 henry we have:

$$T'_{s1} = \frac{2\pi}{10^3}\sqrt{0.00604 \times C'_{s1}} \text{ and } T'_{s2} = \frac{2\pi}{10^3}\sqrt{0.00604 \times C'_{s2}}$$

from these relations follows:

$$C'_{s1} = \frac{0.0477 \times 0.00005486}{0.00604} \text{ mfd. and}$$

$$C'_{s2} = \frac{0.0477 \times 0.00001116}{0.00604} \text{ mfd.}$$

Hence

$$C'_{s1} - C'_{s2} = \frac{0.0477}{0.00604} \times (0.00005486 - 0.00001116)$$

$$= \frac{0.0477}{0.00604} \times 0.0000437 \text{ mfd, or}$$

$$C'_{s1} - C'_{s2} = \frac{9 \times 0.0477 \times 4.37}{0.00604} \text{ centimeters} = \mathbf{310.6 \ cm.}$$

very nearly the same value.

It is to be expected that the value found with a quicker vibrating system should be smaller since then the structure begins to act not as one condenser but as a series of condensers or distributed capacity, all parts not being charged at the same time.

This method of determining the capacity implies therefore to be quite correct a *slow* vibration and, furthermore, negligible capacity in the vibrating system itself and also that the body the capacity of which is determined should not be of too great length since this must cause errors.

From reading with coil of 550 turns it follows, since the capacities both in the primary and secondary circuits remained the same, that the inductances in the primary and inductances in the secondary or excited circuit bore the same ratio, that is:

$$\frac{\text{Ind. } 8\ 7/8 \text{ turns} + \text{conn.}}{\text{Ind. } 3.5 \quad \text{turns} + \text{conn.}} = \frac{\text{Ind. coil } 550 \text{ turns}}{\text{Ind. coil } 344 \text{ turns}}$$

Ind. of coil 550 turns was: 18,650,000

Ind. of coil 344 turns was: 6,040,000

Hence $\dfrac{\text{Ind. } 8\ 7/8 \text{ turns}}{\text{Ind. } 3\ 1/2 \text{ turns}} = \dfrac{1865}{604}$ **This for later comparison.**

Colorado Springs

Nov. 8, 1899

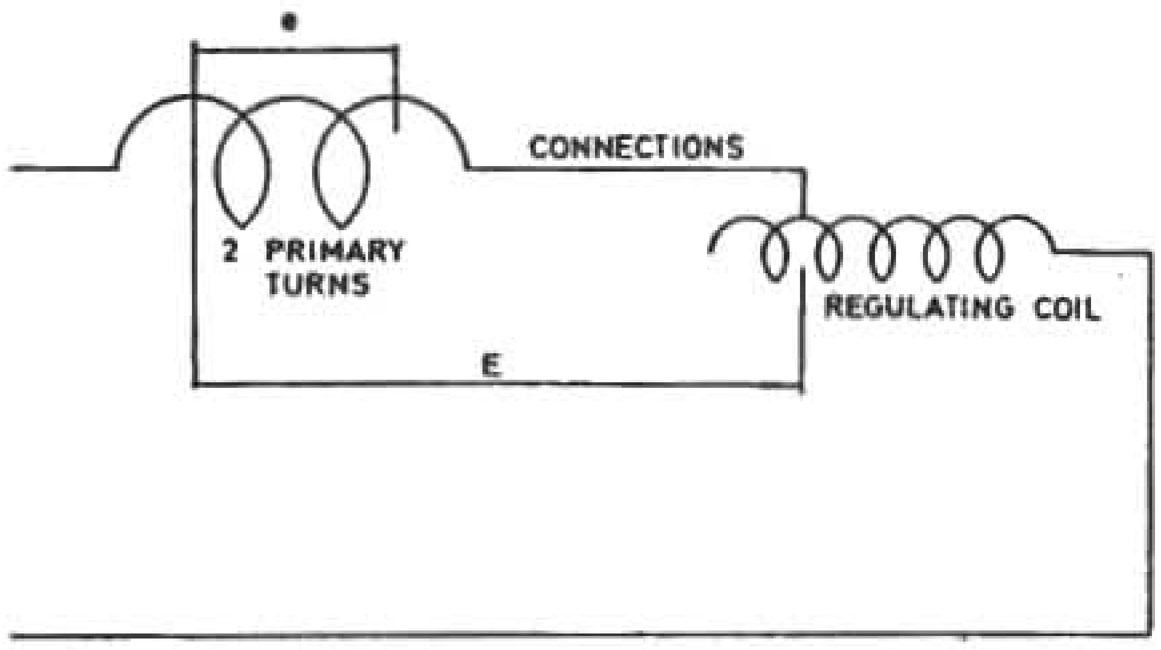
Table of *inductances* prepared from preceding readings.

Two primary turns in series	230,945 cm.	0.000230945 H
One of the primary turns	57,736 "	0.000057736 "
All connections to condensers and breaks *as used*	5004 "	0.000005004 "
All connections plus one half turn of reg. coil (first turn)	5774 "	0.000005774 "
All connections plus the whole first turn of reg. coil	6544 "	0.000006544 "
" " 1 1/2 " "	7314 "	0.000007314 "
" " 2 " "	8084 "	0.000008084 "
" " 2 1/2 " "	8854 "	0.000008854 "
" " 3 " "	10,009 "	0.000010009 "
" " 3 1/2 " "	11,164 "	0.000011164 "
" " 4 " "	12,319 "	0.000012319 "
" " 4 1/2 " "	13,474 "	0.000013474 "
" " 5 " "	15,158 "	0.000015158 "
" " 5 1/2 " "	16,842 "	0.000016842 "
" " 6 " "	18,526 "	0.000018526 "
" " 6 1/2 " "	20,210 "	0.000020210 "
" " 7 " "	21,894 "	0.000021894 "
" " 7 1/2 " "	23,578 "	0.000023578 "
" " 8 " "	25,262 "	0.000025262 "
" " 8 1/2 " "	26,946 "	0.000026946 "
" " 9 " "	28,870 "	0.000028870 "
" " 9 1/2 " "	30,794 "	0.000030794 "
" " 10 " "	32,718 "	0.000032718 "
" " 10 1/2 " "	34,642 "	0.000034642 "

* This table is close enough for all general estimates.

After 10 1/2 turns the increase is 3850 cm. per turn so that the inductance of $10\ 1/2+n$ turns+conn. will be $34{,}642+n\times 3850$ cm. With the entire coil in, there are 23 1/2 turns having 84,692 cm. or 0.000084692 H.

In order to test the accuracy of the preceding measurements, readings of the e.m.f. across the two primaries, connections and the regulating coil — all joined in series — were taken repeatedly and in as rapid a succession as was found practicable, the number of the turns of the regulating coil being varied after each set of readings. The diagram below shows the connections of the various inductances while the readings, reduced to the same e.m.f. across: [the two primary turns+connections +1/2 of one turn of the regulating coil+flexible cable] are given in table below:



Number of turns of the regulating coil included in circuit.	E.m.f. across two primary turns plus the connections, plus flexible cable+one half of one turn reg. coil					Difference of e.m.f. between successive readings:
	first series of readings	second series	third series	fourth series	average	
23 1/2	15.873	15.928	15.928	15.928	15.914	0.208
22 1/2	15.706	15.706	15.706	15.706	15.706	0.396
20 1/2	15.318	15.263	15.34	15.318	15.310	0.399
18 1/2	14.929	14.8185	14.929	14.929	14.901	0.4155
16 1/2	14.4855	14.4855	14.4855	14.4855	14.4855	0.3835
14 1/2	14.119	14.0415	14.1525	14.097	14.102	0.352
12 1/2	13.764	13.7085	13.764	13.764	13.75	0.3745
10 1/2	13.3755	13.3755	13.3755	13.3755	13.3755	0.3635
8 1/2	13.0425	12.9537	13.009	13.0425	13.012	0.3164
6 1/2	12.7095	12.654	12.7095	12.7095	12.6956	0.3191
4 1/2	12.3765	12.3765	12.3765	12.3765	12.3765	0.2221
2 1/2	12.1545	12.1212	12.1875	12.1545	12.1544	0.1544
1/2	12.00	12.00	12.00	12.00	12.00	

e was in these readings smaller than 880.

Note: When reduced to the same e.m.f. across the two primaries and connections, 1/2 turn and flexible cable the average values agree fairly well with the readings before recorded. The table prepared on the bases of the values before found will be accurate enough for all ordinary estimates. Both sets of readings show that there is about 0.2 volt variation per turn, the few first turns excepted.

Following readings were taken today for the purpose of putting together a table of the inductances of the various turns of the regulating coil. The machine was specially run and all care was taken to get the readings as close as practicable. The method used in a previous case was again adopted which consisted in reading the e.m.f. across the two primary turns in series and simultaneously the e.m.f. across the two primary turns+ +connections+the turns in the regulating coil. The resistances as before stated being entirely negligible, the inductance in each case was given by the ratio of the e.m. forces and the known inductance of the two primary turns. By this method the error which might have been caused by a variation of ω which could only be determined by taking the speed of the generator, the apparatus for the more exact determination of this quantity being unfortunately left in New York. The results are indicated in the following table:

E.m.f. across two primary turns in series	E.m.f. across two primary turns+ connections+turns of the regulating coil	Number of turns reg. coil	I	ω	Increase of e.m.f. from step to step
12.00	12.3	1/2	58.8	880	
12.00	12.45	2 1/2	58.8	,,	0.15
12.00	12.70	4 1/2	58.8	,,	0.25
12.00	13.05	6 1/2	58.8	,,	0.35
12.00	13.40	8 1/2	58.8	,,	0.35
12.00	13.80	10 1/2	58.8	,,	0.40
12.00	14.20	12 1/2	58.8	,,	0.40
12.00	14.60	14 1/2	58.8	,,	0.40
12.00	15.00	16 1/2	58.8	,,	0.40
12.00	15.40	18 1/2	58.8	,,	0.40
12.00	15.80	20 1/2	58.8	,,	0.40
12.00	16.20	22 1/2	58.8	,,	0.40
12.00	16.40	23 1/2	58.8	,,	0.20

This shows an increase per turn of about 0.20 V, except the few first turns.

Colorado Springs

Nov. 9, 1899

In some experiments it was necessary to use vibrations of lower frequencies and this made it necessary to insert additional inductances in the condenser discharge circuit. In such cases it was convenient to use the two primary turns only; in order to prevent a strong sparking on the secondary and changing reaction on the primaries it was necessary to join the ends of the secondary. Readings were taken to determine more closely the inductance of the primaries with the secondary closed.

The results were as follows:

Current	E.m.f. across two primary turns in series		ω
58.80		8.75	880
58.40		8.5	"
58.00		8.33	"
Average 58.40	Average	8.45 (with allowance for zero displacement)	880

With the secondary open the readings were exactly as before:

58.8	11.95	880

Reduced to same current for both cases the readings with secondary closed become:

58.8	8.5	880

The inductance of two primary turns as before found 230,945 cm.$=L$. We have for their inductance with *secondary closed* $\frac{8.5}{11.95}L=$**164,270 cm.**

With both primaries in multiple it ought to be **41,068 cm.** approx.

According to previous estimates the mutual induction coefficient with two primaries in series was: approximately 850,000 cm. The inductance of the secondary was found: 9,568,000 cm. last time, say average of two last determinations 9,560,000 cm. From this data we have for inductance with secondary closed:

$$L-\frac{M^2}{N}=230{,}945-\frac{85^2\times 10^8}{956\times 10^4}=230{,}945-\frac{85^2\times 10^4}{956}=230{,}945-75{,}575=\mathbf{155{,}370\ cm.}$$

These readings above do not quite agree with the result calculated, but I think this only indicates some action of secondary on the primary when the former *is open*, or else the mutual induction coeff. measured a little *too high*. This **very likely.**

As it was not always possible to get along with the primaries alone when using them as inductances two self-induction coils were provided, one wound with wire No. 6, the other with wire No. 2 both on a drum of 5″ diam. The particulars relating to both of these coils will be given below. To ascertain approximately their inductances readings were taken by joining them successively in circuit with the two primary cables in series and taking the e.m.f. across, this giving the inductance of each of them approximately from the ratio of the e.m.f. and the known inductance of the primaries, neglecting, of course, the resistance. The readings were as follows:

For coil wound with No. 6 wire:

E.m.f. across two primary turns+coil all in series	E.m.f. across two primaries in series alone	Current	ω
14.5	6.4	30.9	880
14.5	6.4	30.9	880
14.5	6.4	30.9	880

For coil with No. 2 wire:

13.5	8.2	40.1	880
13.5	8.2	40.1	880
13.5	8.2	40.1	880

This would give approximately inductances of coil No. 6 wire:

$$l=\frac{14.5}{6.4}\times 230{,}945-230{,}945=\frac{8.1}{6.4}\times 230{,}945=\mathbf{292{,}290\ cm,}$$

Coil No. 6 wire

and for coil No. 2 wire

$$l_1=\frac{13.5}{8.2}\times 230{,}945-230{,}945=\frac{5.3}{8.2}\times 230{,}945=\mathbf{149{,}340\ cm,}$$

Coil No. 2 wire

These figures were first utilised then separate readings were taken. All the particulars of these coils and the measured and calculated values are as follows:

Coil wound with No. 6 wire:
length of wound part 38.75″=98.425 cm, drum 5″=12.7 cm. 129 turns
Thickness of wire with insulation $\frac{98.425}{129}$ cm. Thickness of bare wire=0.162″=0.41148 cm.
Thickness of two insulations $\frac{98.425}{129}$—0.41148=0.763—0.4115=0.3515 cm. This is to be added to the core 12.7 cm diam. making total diam. 13.0515 cm.

To calculate inductance we have therefore the following data:

$d=13.0515$ cm, $l_1=98.425$ cm, $N=129$, $N^2=16641$, $S=\frac{\pi}{4}d^2=133.786$ cm.sq.

This gives $l=\frac{12.5664}{98.425}\times 16{,}641\times 133.786=\mathbf{284{,}247\ cm.}$

Now the readings to estimate from were:

e.m.f.	Current	ω	R calculated approx. 180 feet wire 2535ft. per ohm	$\frac{E}{I}=0.271$ $\left(\frac{E}{I}\right)^2=0.073441$
13.3	49.1	880		
13.3	49.1	880	0.071 ohm	$R^2=0.00504$
13.3	49.1	880		$\left(\frac{E}{I}\right)^2-R^2=0.0684$

from this:

$$l=\frac{\sqrt{0.0684}}{880}=\frac{0.2615}{880}\,\mathrm{H} \text{ or } \frac{261{,}500{,}000}{880}=\mathbf{297{,}160\ cm.}$$

Small correction should have been made for the e.m.f. making it smaller, this would have made the agreement with the calculated value close.

Coil wound with No. 2 wire

Readings were:

e.m.f.	Current	ω	Resistance will be negligible
6.6	49.1	880	
6.6	49.1	880	
6.6	49.1	880	

$$l_1=\frac{E}{I\omega}=\frac{6.6}{49.1\times 880}=\frac{6.6}{491\times 88}\,\mathrm{H}$$

$$\text{or}=\frac{66\times 10^8}{491\times 88}\,\mathrm{cm.}$$

$$=\mathbf{152{,}750\ cm.}$$

The dimensions are as follows:

diam. core $5''=12.7$ cm, length of core $38.25''=97.185$ cm. Turns 91. The diam. of wire insulation is $\frac{97.185}{91}=1.068$ cm. Diam. of bare wire $0.2576''=0.6543$ cm. This gives for 2 thicknesses $1.068-0.6543=0.4137$ cm.

From this:

$$d=13.1137\ \text{cm.};\qquad l'=97.185\ \text{cm};\qquad N=91;\qquad N^2=8281;$$

$$S=\frac{\pi}{4}d^2=145.0644\ \text{sq.cm.}\qquad l_1=\frac{4\pi}{l'}N^2S=\mathbf{155{,}330\ cm.}$$

Probably resistance is not quite negligible, but results are close enough for ordinary use of coil.

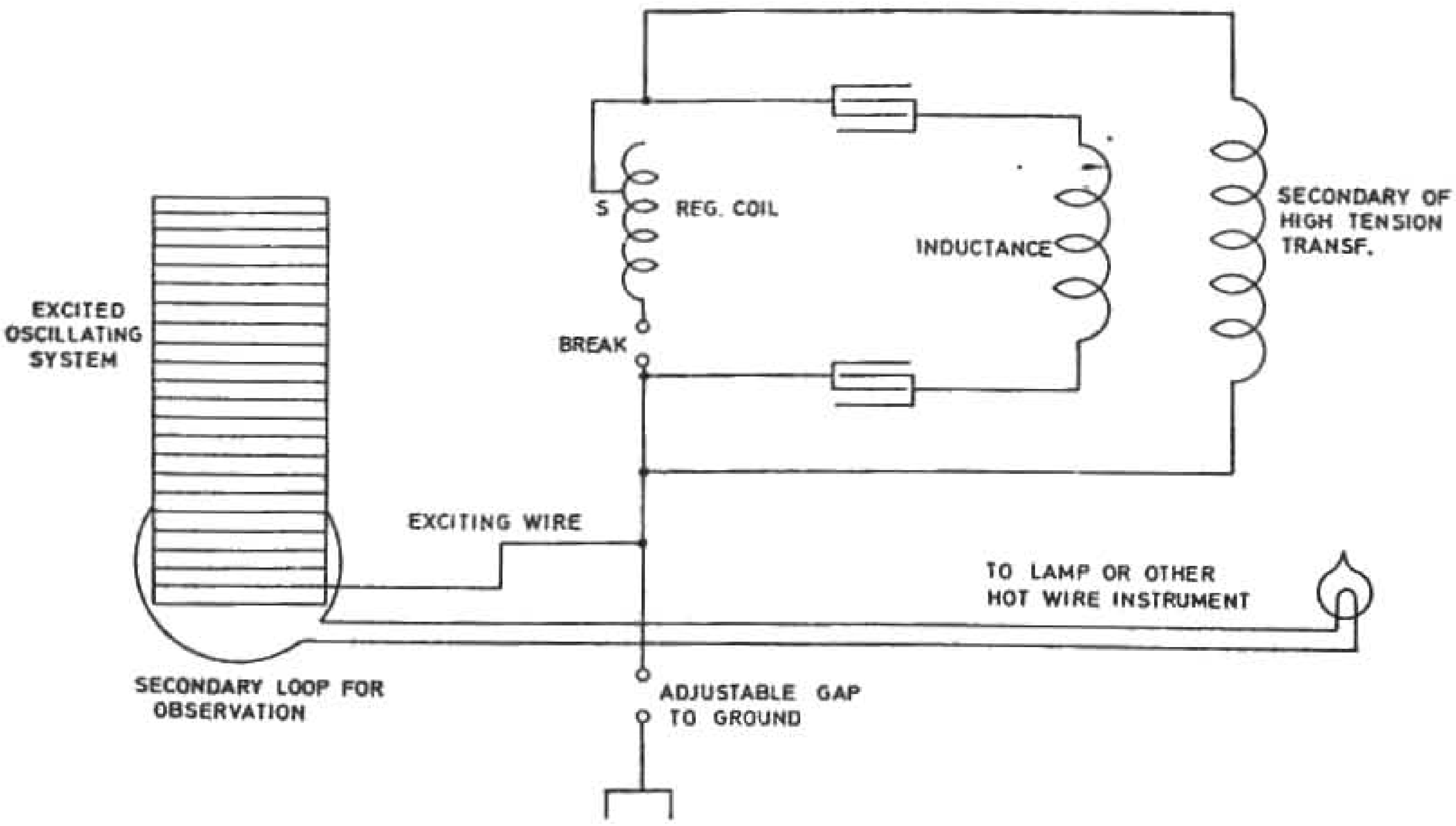
Colorado Springs

Nov. 10, 1899

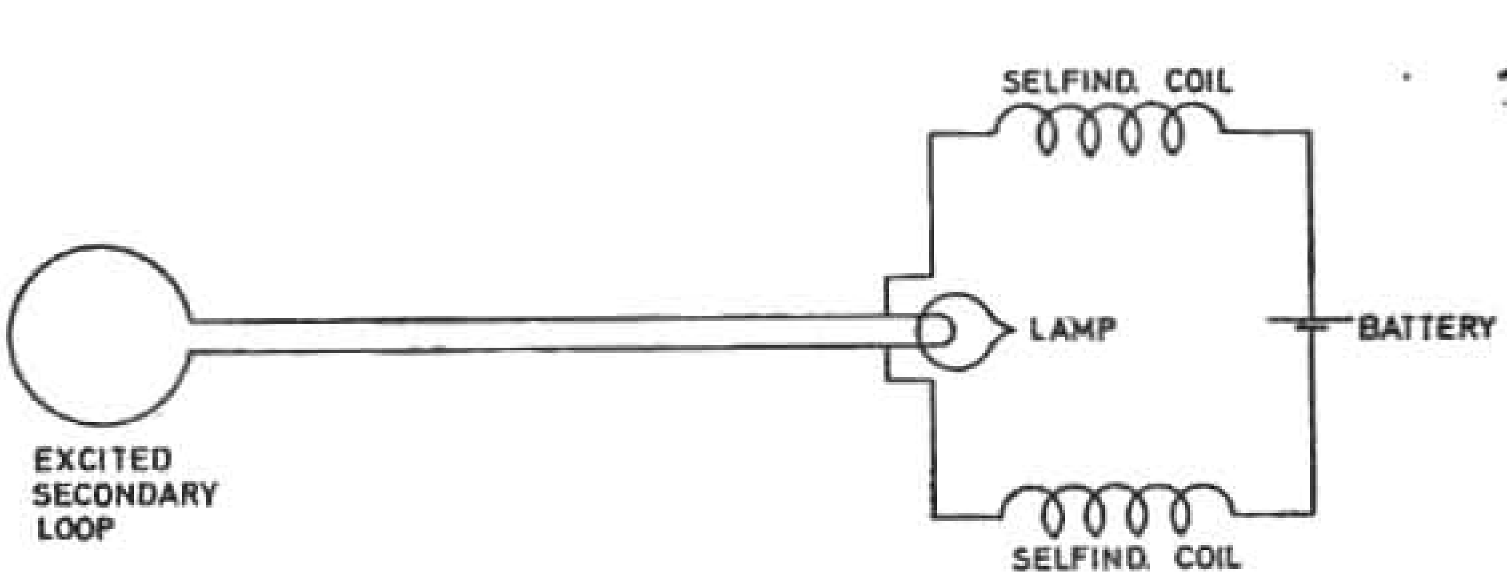
Measurements of the effective capacity of a vertical wire as modified by elevation, by resonance analysis and improved method of locating the maximum rise of e.m.f. on the excited system.

In the previous experiments on the same subject the maximum was located by observing a spark, but it was found that this mode of reading has a number of defects. One of these is the necessity of using spark wires, another the impossibility of locating the maximum very closely — except in cases when the tuning is very sharp. But when considerable capacity is in the system, as it must necessarily be when investigating the modification of capacity, the tuning can never be quite sharp. When the pressures on the excited coil are large spark wires also entail considerable loss, which modifies and vitiates the results of the observations. By the spark method it is also impossible to determine the period and capacity of the excited system itself without any attachments.

In the succeeding observations a method practised in New York was resorted to. This consists of employing a small secondary circuit in feeble inductive connection with the excited system and observing in a convenient manner by a suitable instrument the changes of current or e.m.f. in the secondary. A practical and quite convenient means is to insert a minute lamp consuming but a very small fraction of the normal current and observe the degree of incandescence of the minute carbon filament or thin platinum wire. As the small secondary circuit excercises no appreciable reaction on the excited oscillating system owing to the feeble mutual induction and minute amount of energy consumed in the se-



condary, the method is excellent and allows close and reliable readings much more so than the spark wire method. By taking a minute lamp with an exceptionally thin and short filament the energy consumed for the readings is quite insignificant and may be less than one millionth part of the activity of the oscillating system. In the diagram below the arrangement of apparatus as used is illustrated. The excitation was again conveniently varied by an adjustable ground gap. In the secondary circuit feeding the minute lamp it was also of advantage to provide a *continuously* regulable resistance by means of which the brightness of the filament could be reduced to any degree desired. The current from the supply transformer was also regulable as this was necessary in the course of the experiments. Usually I find it advantageous to proceed as follows: first the maximum is located on the proper place of the regulating coil by altering the capacity of the primary circuit until the maximum rise takes place with the contact slide S at the desired point of the regulating coil. A few turns to either side will generally extinguish the lamp. The maximum being thus roughly located, the brightness of the lamp is reduced by inserting resistance or otherwise — as by placing the secondary circuit feeding it farther from the excited system — until the filament is barely visible when the slide S is at the point giving the maximum rise on the excited system. By a little experience it becomes easy to thus locate the maximum within 1/4 of one per cent. By resorting however to ordinary experimental resources it is practicable to reach greater precision still. Of course, the greater the momentum of the excited system the better it is. There are hot wire instruments or detectors of all kinds which allow the method to be refined to any degree desired. A very simple improvement, effective and readily on hand is however to provide a source of energy for bringing the filament or wire just to a point when its luminosity can be detected by the observer. I connect the lamp to a battery of constant e.m.f. through two chocking coils graduating the turns of the latter so that the filament is brought preliminarily to the required temperature. A small amount of surplus energy supplied from the secondary loop is then sufficient to make the filament bright. Thus, less energy is taken from the excited system and the location of the maximum is rendered much more easily. The diagram below illustrates this arrangement in its simplest form. The high frequency currents can not of course pass through the chocking coils. This method is also very suitable for tuning circuits for many purposes as in telegraphy.



In the present experiments the coil before described: 1314 turns wire No. 18 on drum 14" diam., 8 feet long was used, the object of the tests being to determine the effective capacity of the vertical wire No. 10, 50 feet long which was used in a number of cases before dwelt upon. The readings were as follows:

Coil 1314 turns with spark wires as before used

Capacity in primary circuit	Inductance in primary circuit
$\frac{46}{2}$=23 bottles=0.0207 mfd.	16 Turns of regul. coil+connections+coil No. 6 wire

Note: This reading was taken to test the spark wire method. The agreement was fairly close *15 1/2* turns being found in the previous measurements by spark analysis instead of *16* turns as now. But this was to be expected as with the *spark wires alone*, the capacity being small the tuning is very sharp. The agreement would probably not be quite so close when a large capacity is connected to the excited system.

Coil 1314 turns alone without spark wires

$\frac{20}{2}$=10 bottles=0.009 mfd.	12 1/2 turns+conn.+coil No. 6 wire

Coil 1314 turns with vertical wire No. 10 approx. 50 feet long

$\frac{70}{2}$=35 bottles=0.0315 mfd. 18 1/2 turns+conn.+coil No. 6 wire

The inductance of primary circuit in the first case was:

Coil No. 6 wire	284,000 cm	total 326,300 cm.
12 1/2 turns+conn.	42,300 ,,	

In the second case it was:

Coil No. 6 wire	284,000 cm	total 349,400 cm.
18 1/2 turns+conn.	65,400 ,,	

Calling as before C_{s1} and C_{s2} respectively the capacities of the excited system with and without the vertical wire we have:

$$C_{s1}=\frac{873,000,000}{10^9}=\frac{349,400}{10^9}\times 0.0315$$

* the inductance of excited coil from data obtained before being 87,300,000 cm.

$$C_{s1}=\frac{3494\times 0.0315}{873,000}\text{ mfd.}$$

Similarly from the preceeding it follows:

$$C_{s2}=\frac{3263\times 0.009}{873,000}\text{ mfd.}$$

This gives the capacity of the vertical wire:

$$C_{s1}-C_{s2}=\frac{3494\times 0.0315-3263\times 0.009}{873,000}=$$

$$=\frac{110.061-29.367}{873,000}=\frac{80.694}{873,000}\text{ mfd,}$$

or in centimeters:

$$C=C_{s1}-C_{s2}=\frac{9\times 10^5\times 80.694}{873,000}=\frac{72,624.6}{873}=\mathbf{83.2}\text{ cm.}$$

The calculated value before found was **81.5 cm.** It is assumed in the calculation that the length of the wire was 50 feet exactly, but this might not be so. It will be measured exactly when taken down. The inductance of the coil with wire No. 6 has been taken as 284,000 cm. but the measured values are higher. Taking the average of two measurements we have about 295,000 cm. This would give a higher value for the effective capacity of the vertical wire. It is also possible that the inductance of the excited coil might be a few percent different from that serving as the basis of this estimation.

It is of interest to determine from above data the capacity of the excited coil alone. The same is:

$$C_{s2}=\frac{3263\times 0.009\times 9\times 10^5}{873,000}=\mathbf{30.3\ cm,\ approx.}$$

A cylinder of the dimensions of the coil excited would have a capacity $C=\dfrac{l}{2\log_e \frac{l}{r}}$.

Here $l=8'=243.84$ cm. $r=7''=17.78$ cm.

$$\frac{l}{r}=13.71 \qquad \log_e \frac{l}{r}=1.137037\times 2.3=2.6152$$

$$C=\frac{243.84}{2\times 2.6152}=46.6 \text{ cm.}$$

Consider now as much of the cylindrical surface as could be covered with the bare wire on the coil:

No. 18 wire diam.$=0.0403''=0.1024$ cm. As there are 1314 turns the wire would cover 1314×0.1024 cm$=134.55$ cm.

Compared with the cylinder of the length of 243.84 cm the capacity C_1 of the shortened would be in the proportion of 134.55 : 243.84 reduced, that is

$$C_1 \text{ would be } \frac{134.55}{243.84} \qquad C=\frac{134.55}{243.84}\times 46.6=\text{approx. } \mathbf{26\ cm.}$$

From this it would seem that a rough estimate of the capacity of such a coil might be obtained by comparison with a cylindrical surface which the bare wire would cover.

Further experiments to ascertain the dependence of capacity upon elevation.

In these experiments the new coil, wound with a much greater number of turns for the purpose of getting a vibration of lower frequency, was used. This coil was wound on the same drum of 14″ diam. and 8 feet length repeatedly used. It had 1314 turns of No. 18 wax covered wire. As the length of the coil and area of the coils remained exactly the same the self-induction was approximately estimated from the inductance of another coil experimented with before. The latter had 689 turns and its measured inductance was 24,000,000 cm. On this basis the inductance of the new coil was $L\left(\frac{1314}{689}\right)^2=?$, L being the self-nduction of the coil referred to. This would give for $L_1=\left(\frac{1314}{689}\right)^2\times 24{,}000{,}000=3.637\times$ $\times 24{,}000{,}000=87{,}288{,}000$ cm approximately. Comparing it with another coil before described which was wound on the same drum and had 346 turns, and taking the before measured value of the inductance of the latter 6,040,000 cm we get

$$L_1=\left(\frac{1314}{346}\right)^2\times 6{,}040{,}000=14.4225\times 6{,}040{,}000=87{,}111{,}900 \text{ cm.}$$

which is very nearly the same value.

Rough readings gave:

$$E=200 \qquad I=2.5 \qquad \omega=870$$

from this: $\frac{E}{I}=80$ $\quad$ $\left(\frac{E}{I}\right)^2=6{,}400$

$$R^2=942.5$$

$$\left(\frac{E}{I}\right)^2-R^2=5457.5$$

R calculated: 4816 feet wire No.18
156.9 feet per ohm: $R=30.7$ ohm
(31.68 meas.)

$$\sqrt{\left(\frac{E}{I}\right)^2-R^2}=73.88 \text{ approx.}$$

Inductance nearly **85,000,000 cm.**

For the present investigation the most probably value 87,300,000 cm will be adopted, which is still to be verified.

With the coil before described experiments were made for the purpose of once more determining the capacity of the structure of iron pipes. The adjustments were as follows:

For coil with structure connected to free terminal:

Capacity in primary circuit

Inductance of primary circuit
21 turns regulating coil+conn.+coil wound with wire No. 6 before described

$$\frac{(6\times 36)-2+12}{2}=113 \text{ bottles}=0.1017 \text{ mfd}$$

For coil with the spark wires alone:

$\frac{46}{2}=23$ bottles$=0.0207$ mfd

15 1/2+conn+coil No. 6 wire.

In the first case inductance of the primary was =359,000 cm.
$\left\{\begin{array}{ll}\text{Coil No. 6 wire} & 284{,}000 \text{ cm.}\\ \text{21 turns+conn.} & 75{,}000 \text{ ,,}\end{array}\right\}$

In the second case $\left\{\begin{array}{ll}\text{Coil No. 6 wire} & 284{,}000 \text{ cm}\\ \text{15 1/2 turns+conn.} & 54{,}000 \text{ ,,}\end{array}\right\}=338{,}000$ cm.

Calling C_{s1} capacity of the excited system in first and C_{s2} in the second case we have:

$$\frac{2\pi}{10^3}\sqrt{\frac{87{,}300{,}000}{10^9}C_{s1}}=\frac{2\pi}{10^3}\sqrt{\frac{359{,}000}{10^9}\times 0.1017} \text{ and}$$

$$C_{s1}=\frac{\frac{359}{10^6}\times 0.1017}{\frac{873}{10^4}}=\frac{359\times 0.1017}{87{,}300} \text{ mfd}$$

$$\text{or in cm } C_{s1} = \frac{9 \times 10^5 \times 359 \times 0.1017}{87,300} = \mathbf{376.4\ cm.}$$

Similarly we have: $\frac{2\pi}{10^3}\sqrt{\frac{87,300,000}{10^9}C_{s2}} = \frac{2\pi}{10^3}\sqrt{\frac{338,000}{10^9} \times 0.0207}$ and

$$C_{s2} = \frac{338,000 \times 0.0207}{87,300,000} \text{ mfd or } C_{s2} = \frac{338 \times 0.0207 \times 9 \times 10^5}{87,300} \text{ cm.}$$

$$= \frac{3042 \times 20.7}{873} = \mathbf{71.67\ cm.}$$

From this we get *effective capacity* of structure:

$$C_{s1} - C_{s2} = 376.4 - 71.67 = \mathbf{304.73\ cm,}$$

which is a value very closely before found with *extra coil.*

Note: The readings with spark gap as before practiced are not quite satisfactory and a new method will be tried in the next experiments.

Colorado Springs

Nov. 11, 1899

Experiments for the purpose of ascertaining rate of increase of capacity with elevation continued.

Again the coil with 1314 turns described before was used and the method of locating the maximum rise of potential on the excited system by means of a small circuit inductively connected to the system was resorted to. A few improvements carried out in the mode of using the induced circuit allowed closer readings than it was possible to obtain before with spark observation.

The coil was first tuned alone, without anything being attached to the free terminal. Next the vertical wire No. 10, 50 feet long (approximately) was attached to the free terminal and the tuning again effected, both the primary vibrations being carefully noted. Then a ball 30″ diam. was slipped on to the vertical wire and readings were taken in three different positions of the ball along the wire as before. The results of the observations were as follows:

I. Coil alone

Capacity in primary or exciting circuit	Inductance in primary circuit
$\frac{20}{2}$=10 bottles=0.009 mfd	Turns of reg. 13 coil+conn+coil
	No. 6 wire

II. Coil with vertical wire No. 10, 50 feet approx.

$\frac{72}{2}$=36 bottles=0.0324 mfd 17+conn.+coil No. 6 wire

III. Coil with ball 30" diam. vertical wire, the ball being at a height of 10'3" from center to ground.

$\frac{86}{2}$=43 bottles=0.0387 mfd 13 1/2+ ,, + ,,

IV. Coil with ball 30" diam. and vertical wire, the ball being at a height of 34 feet from center to ground.

$\frac{86}{2}$=43 bottles=0.0387 mfd 14 1/2+ ,, + ,,

Note: (it seemed slightly more than 14 1/2 turns)

V. Coil with ball 30" diameter and vertical wire, the ball being at a height of 57'9" from center to ground.

$\frac{86}{2}$=43 bottles=0.0387 mfd 16 1/2+ ,, + ,,

In the first case the inductance of primary circuit was

Coil No. 6 wire	=295,000 cm
13 turns+connections	= 43,300 ,,
total	=338,300 cm.

The primary vibration was therefore:

$$T_{p1}=\frac{2\pi}{10^3}\sqrt{0.009\times\frac{3383}{10^7}}$$

Now calling C_{s1} capacity of excited system in the first case we have:

period of excited system

$$T_{s1}=\frac{2\pi}{10^3}\sqrt{C_{s1}\times\frac{85}{10^3}}$$

Note: In some estimates before the inductance of this coil was calculated to be a little over 284,000 cm. and this value was taken. But two measurements made before show average of about 295,000 cm. and this value will be assumed in present estimates as being more probable until again careful measurements will be made. The results are then to be corrected.

Note: The inductance for excited coil is taken 85,000,000 cm., this being the value obtained by measurement.

Still to be verified.

From this:

$$C_{s1} = \frac{0.009 \times \frac{3383}{10^7}}{\frac{85}{10^3}} = \frac{0.009 \times 3383}{85 \times 10^4} \text{ mfd, or in centimeters:}$$

$$C_{s1} = \frac{9 \times 10^5 \times 0.009 \times 3383}{85 \times 10^4} = \frac{0.81 \times 3383}{85} = \mathbf{31.84\ cm.}$$

This is slightly larger than before found owing to adoption of smaller inductance for excited coil.

In case II. the inductance of the primary circuit was:

$$\left.\begin{cases} \text{Coil No. 6 wire as before:} & 295{,}000 \text{ cm} \\ \text{17 turns+connections} & 59{,}700 \text{ ,,} \end{cases}\right\} \text{total}=354{,}700 \text{ cm.}$$

The primary period was:

$$T_{p2} = \frac{2\pi}{10^3}\sqrt{0.0324 \times \frac{3547}{10^7}} \text{ and the secondary corresponding } T_{s2} = \frac{2\pi}{10^3}\sqrt{C_{s2} \times \frac{85}{10^3}}$$

Hence $C_{s2} = \frac{0.0324 \times 3547}{85 \times 10^4}$ mfd, or $C_{s2} = \frac{9 \times 10^5 \times 0.0324 \times 3547}{85 \times 10^4}$ cm.

C_{s2}=**121.68 cm.** Hence capacity of the vertical wire will be approximately

C_{s2}—C_{s1}=**89.84 cm.** This is again larger than before found but probably closer than the former value.

In case III. the primary inductance was:

$$\left.\begin{cases} \text{Coil No. 6 wire} & 295{,}000 \\ \text{13 1/2 turns+conn.} & 46{,}200 \end{cases}\right\} \text{total } 341{,}200 \text{ cm.}$$

The primary vibration was therefore:

$$T_{p3} = \frac{2\pi}{10^3}\sqrt{0.0387 \times \frac{3412}{10^7}}$$

and the corresponding vibration of the excited system

$$T_{s3} = \frac{2\pi}{10^3}\sqrt{C_{s3} \times \frac{85}{10^3}}$$

from this we have:

$$C_{s3} = \frac{0.0387 \times \frac{3412}{10^7}}{\frac{85}{10^3}} = \frac{0.0387 \times 3412}{85 \times 10^4} \text{ mfd,}$$

or

$$C_{s3} = \frac{9 \times 10^5 \times 0.0387 \times 3412}{85 \times 10^4} = 139.81 \text{ cm.}$$

The effective capacity of the ball at its lowest position (10′ 3″) from ground was therefore only $C_{s3}—C_{s2}$=139.81—121.68=**18.13 cm.**

Now taking cases IV. and V. the primary inductance in the

first of these cases was $\left\{\begin{array}{ll} \text{Coil No. 6 wire} & 295{,}000 \text{ cm} \\ 14\ 1/2 \text{ turns} & 50{,}100 \text{ ,,} \end{array}\right\}$

the total would be **345,100 cm.** But there is still a doubt whether there have not been 15 turns instead of 14 1/2. This is to be borne in mind. Taking for the present for the inductance 14 3/4 turns as most probable and nearer to the average value of both extreme readings in IV. and V. we have for inductance of the primary **346,000 cm.**

Now in case V. the inductance was: $\left\{\begin{array}{ll} \text{Coil No. 6} & 295{,}000 \text{ cm} \\ 16\ 1/2 \text{ turns} & 57{,}800 \text{ ,,} \end{array}\right\}$

total **352,800 cm.**

Now since in cases III, IV. and V. the capacity in the primary circuit was not varied we have:

$$C_{s3} : C_{s4} = 341{,}200 : 346{,}000 \text{ and } C_{s4} = C_{s3} \times \frac{346}{341} = \mathbf{141.78} \text{ cm.}$$

and similarly we have:

$$C_{s3} : C_{s5} = 341{,}200 : 352{,}800 \text{ and } C_{s5} = C_{s3} \times \frac{3528}{3412} = \mathbf{144.56} \textbf{ cm.}$$

The effective capacity of ball at its highest position was:

$$C_{s5} — C_{s2} = 144.56 — 121.68 = 22.88 \text{ cm.}$$

In the mean position the value was: $C_{s4}—C_{s2}$=**20.1 cm.** whereas the mean value between 22.88 and 18.13 would be **20.5 cm.** The rise is therefore *linear*. The rise in the effective capacity for 47 feet and 6″ was $\frac{18.13}{22.88-18.13}$ about 26.2%. Per one *hundred feet* it would be from this: 55.16% or a little over 1/2% per foot.

Colorado Springs

Nov. 12, 1899

Measurements of the effective capacity of the elevated structure of iron pipes were again made today in the manner described before, by means of resonance analysis, the maximum rise of potential on the excited system being determined by a minute lamp included in a secondary circuit without appreciable reaction upon the excited system. The coil with 1314 turns before described was again used, the readings being as follows:

Coil with structure attached:

Capacity in primary circuit	Inductance in primary circuit turns reg. coil
$\frac{(6 \times 36) + 12}{2} = \frac{228}{2} = 114$	15+conn.+coil No. 6 wire
bottles or 0.1026 mfd.	

Coil alone, without structure, only connecting wire:

$\frac{(36 - 6) + 12}{2} = \frac{42}{2} = 21$	7 1/2+ „ + „
bottles=0.0189 mfd	

The inductance in primary in first case was:

Coil No. 6 wire	295,000
15 turns+conn.	52,000
total	347,000 cm.

The inductance in primary in second case was:

Coil No. 6 wire	295,000 cm.
7 1/2 turns+conn.	23,600 „
total	318,600 cm.

If C_{s1} and C_{s2} be the capacities of the excited system *with* and *without* structure, respectively, then:

$$C_{s1} = \frac{\frac{347,000}{10^9} \times 0.1026}{\frac{87,300,000}{10^9}} = \frac{3470 \times 0.1026}{873,000} \text{ mfd.},$$

and similarly

$$C_{s2} = \frac{3186 \times 0.0189}{873,000}$$

and

$$C_{s1} - C_{s2} = \frac{3470 \times 0.1026 - 3186 \times 0.0189}{873,000} \text{ mfd} = \frac{356.022 - 60.2154}{873,000} \text{ mfd},$$

or

$$\frac{9 \times 10^5 \times 295.8066}{873,000} = \mathbf{304.95\ cm.}$$

This is again a value close to that found with new extra coil. The agreement would be closer still if some connections would be taken in the present instance. I conclude effective capacity is not far from this.

Colorado Springs

Nov. 13, 1899

An improvement in the method of locating the maximum rises in the excited system has been effected by taking a lamp with an exceptionally thin filament, consuming only a minute fraction of an ampere, for being heated to redness enough to be perceptible, and furthermore by placing the lamp in a dark box. A "fluoroscope" was used, two holes being drilled in the sides of the box for leading the wires in. By these provisions the readings were made more exact. The new extra coil was again used for trial and the capacity of the structure of iron pipes was again determined. The readings were:

With structure attached

Capacity in primary circuit	Inductance in primary circuit
$\frac{(8\times 36)}{2}=144$ bottles$=0.1296$ mfd	Turns+connections
	18 1/2+ ,,

Without structure (only connecting wire)

$\frac{(8\times 36)}{2}=144$,, $=0.1296$ mfd	6 5/16+conn.

Note: In the second case the tuning was, of course, very sharp and it was easy to locate the maximum within 1/16 of a turn of the regulating coil; in the first case, although it was naturally less sharp, it was still easy to locate within 1/4 of a turn; with great care within 1/8 of a turn. This may be said to be within 1/2% which is satisfactory, all the more as the reading is very positive.

The above results give an inductance in the primary circuit, in the first case 65,442 cm, in the second 19,578 cm, computed from the table before prepared. As the capacity in the primary remained the same in both readings we have, calling C_{s1} and C_{s2} capacities of the excited system *with* and without structure and L inductance of the extra coil: $L=0.02$ henry

$$C_{s1}-C_{s2}=\frac{0.1296\,(65{,}442-19{,}578)\times 9\times 10^{5}}{20{,}000{,}000}\ \text{cm}=\mathbf{267.48\ cm.}$$

These readings seem most reliable so far.

Colorado Springs

Nov. 14, 1899

In some experiments with coil having 1314 turns wound on drum 14" diam., 8 feet long the coil was cut in the middle and the two parts, 657 turns each connected in multiple. The self-induction was then practically $\frac{1}{4}$ of the self-induction which it had used ordinarily. Readings were taken to determine the inductance when the two parts were connected as stated.

These readings were:

$$\text{e.m.f.} \begin{Bmatrix} 214 \\ 212 \\ 210 \end{Bmatrix} \quad I \begin{Bmatrix} 10.7 \\ 10.6 \\ 10.5 \end{Bmatrix} \qquad \omega=880$$

Average values:		
E	I	ω
212	10.6	880

from this $\left(\frac{E}{I}\right)=20$, $\left(\frac{E}{I}\right)^2=400$

$R=7.9$ ohm.
$R^2=62.41$

$$\left(\frac{E}{I}\right)^2-R^2=337.59 \qquad \sqrt{\left(\frac{E}{I}\right)^2-R^2}=18.375$$

$$L=\frac{18.375\times 10^9}{880}\text{ cm}$$

$=20{,}880{,}682$ cm, approx.$=20{,}881{,}000$ cm.

The inductance of the coil as ordinarily used would then be approx.

$=83{,}524{,}000$ cm.

Colorado Springs

Nov. 15, 1899

Experiments with secondary of oscillator to determine capacity of structure, also capacity of secondary.

The readings were as follows:

Secondary alone.

Capacity in primary	Inductance in primary
$\frac{8\times 36}{2}=144$ bottles$=0.1296$ mfd	14 3/4 turns+connections.

Secondary with connecting wire leading to structure.

$\frac{8\times 36}{2}=144$ bottles$=0.1296$ mfd	15 1/4 „ + conn.

Secondary with structure connected to free terminal.

$\frac{8\times 36}{2}=144$ bottles$=0.1296$ mfd	19 „ + conn.

* These readings approximate.

In first case inductance of primary was 51,000 cm
,, second ,, ,, 52,900 ,,
,, third ,, ,, 67,400 ,,

* All these readings and maybe previous ones to be revised.

Taking the inductance of secondary from measurements before made 9,557,000 cm. we have for C_{s1}, that is, capacity of secondary alone:

$$\left.\begin{aligned} T_{p1} &= \frac{2\pi}{10^3}\sqrt{\frac{51,000}{10^9}\times 0.1296} \\ T_{s1} &= \frac{2\pi}{10^3}\sqrt{\frac{9,557,000}{10^9}\times C_{s1}} \end{aligned}\right\} \quad \begin{aligned} C_{s1} &= \frac{0.1296\times 51,000}{9,557,000} = \frac{0.1296\times 51}{9557} \text{ mfd.} \\ C_{s1} &= \frac{9\times 10^5\times 0.1296\times 51}{9557} = \mathbf{622.23} \text{ cm.} \end{aligned}$$

Now calling C_{s2} and C_{s3} respectively, the capacities of the secondary system with the connecting wire and with wire and structure respectively, since the capacity in the primary was in all cases the same, we have:

$$C_{s1} : C_{s2} = 51,000 : 52,900 \text{ and } C_{s1} : C_{s3} = 51,000 : 67,400$$

and

$$C_{s2} = \frac{52,900}{51,000}\times 622.23 = \frac{529}{510}\times 622.23 = \mathbf{645{,}41} \text{ cm.}$$

This gives capacity of connecting wire alone:

$$C_{s2} - C_{s1} = 645.41 - 622.23 = \mathbf{23.18} \text{ cm.}$$

Similarly we have:

$$C_{s3} = \frac{67,400}{51,000}\ C_{s1} = \frac{674}{510}\times 622.23 = \mathbf{822.32} \text{ cm,}$$

and from this the capacity of the structure (the effective capacity) would be:

$$C_{s3} - C_{s2} = 822.32 - 645.41 = \mathbf{176.91} \text{ cm.}$$

But since

$$C_{s3} : C_{s2} = 67,400 : 52,900 = 674 : 529$$

we have C_{s3}=

$$C_{s3} = \frac{674}{529}\ C_{s2} = \frac{674}{529}\times 645.41 = \mathbf{818.54} \text{ cm.}$$

This value checks those formerly found and shows that the readings were fairly close. The test shows however that this method of determining capacity will only give a correct value when the distributed capacity is quite negligible. This observation has already been made.

Colorado Springs

Nov. 16, 1899

Experiments continued on the influence of elevation upon capacity of system connected to earth.

A new coil wound on drum 14" diam., 8 feet long was used. It had 344 turns No. 10 wire. From the fact that another coil with 346 turns had an inductance of a little over 6,000,000 cm. it is not far away to take the inductance of this coil at that figure.

In the experiments presently described a length of wire No. 12 was used (15 meters long.) The object was to ascertain the capacity of the wire used in connection with the coil. The results of the readings were as follows:

Coil alone without vertical wire.

Capacity in primary circuit	Inductance in primary circuit
$\frac{36}{2}=18$ bottles$=0.0162$ mfd	$4\frac{13}{16}$ turns+connections.

Coil with vertical wire No. 12, 15 meters long.

$\frac{36}{2}=18$ bottles$=0.0162$ mfd	14 3/4 turns+conn.

The inductance in primary in the first case was 14,530 cm. In second case 51,000 cm, approx.

If C_{s1} and C_{s2} be again the capacity of the excited system in the first and second case respectively, we have by analogy from previous experiments:

$$C_{s1}=\frac{\frac{14,530}{10^9}\times 0.0162}{\frac{6,000,000}{10^9}}=\frac{14,530\times 0.0162}{6\times 10^6}\text{ mfd}$$

or

$$C_{s1}=\frac{9\times 14,530\times 0.0162\times 10^5}{6\times 10^6}=\mathbf{35.3\ cm.}$$

Since the capacity in the primary circuit remained the same in both experiments, we have:

$$C_{s1}:C_{s2}=14,530:51,000 \text{ and } C_{s2}=\frac{5100}{1453}\ C_{s1}=\frac{5100}{1453}\times 35.3=\mathbf{121.15\ cm.}$$

Hence the capacity of wire alone

$$C_{s2}-C_{s1}=121.15-35.3=\mathbf{85.85\ cm.}$$

This is the actual or effective capacity of the wire as used with the coil. But the calculated capacity would be

$$C=\frac{l}{2\log_e\frac{l}{r}}$$

Here $l=15$ meters$=1500$ cm. $\frac{l}{r}=7308$

$r=0.08081''=0.20526$ cm.

$$\log_e\frac{l}{r}=3.863799\times 2.3=8.887$$

$$C=\frac{1500}{2\times 8.887}=\frac{1500}{17.774}=\mathbf{84.4\ cm.}$$

According to this estimate the effective capacity would be only about 1.7% larger than the calculated capacity.

Colorado Springs

Nov. 17, 1899

Experiments to ascertain capacity of various lengths of vertical wire.

Coil with 344 turns and No. 10 on drum 14" diam., 8 feet long was used. The wire to be tested was No. 12 of a length of 15 meters. The full length was first connected to the free terminal of the coil excited as usual and then 3 meters were cut off each time and the adjustment of the primary circuit made. The results are indicated below:

Capacity in primary circuit	Length of vertical wire	Inductance in pr. cir.
$\frac{22}{2}=11$ bottles$=0.0099$ mfd	15 meters	21 1/2 turns+conn.
,, ,,	12 ,,	19 ,, + ,,
,, ,,	9 ,,	16 1/4 ,, + ,, 17
,, ,,	6 ,,	13 3/4 ,, + ,, 13 5/8 ,, + ,,
,, ,,	3 ,,	10 1/2 ,, + ,,
,, ,,	0 ,,	7 3/8 ,, + ,,

Approximate estimates from the above readings:

The inductance of coil 344 turns is assumed to be 6×10^6 cm. which is still to be confirmed by close measurement. The inductance of primary when no wire was attached was 7 3/8 turns + conn. = 23,157 cm. With 3 meters wire attached it was 10 1/2 + conn. = = 34,642 cm. Hence calling C_{s1} and C_{s2} the capacities of the excited system, in the two cases respectively we have:

$$T_{p1} = \frac{2\pi}{10^3}\sqrt{0.0099 \times \frac{23157}{10^9}} \qquad C_{s1} = \frac{0.0099 \times 23,157}{6 \times 10^6} \text{ mfd, or in centimeters:}$$

$$T_{s1} = \frac{2\pi}{10^3}\sqrt{\frac{6 \times 10^6}{10^9}\,C_{s1}} \qquad C_{s1} = \frac{9 \times 0.0099 \times 23,157}{60} = \mathbf{34.386} \text{ cm}$$

$$T_{p2} = \frac{2\pi}{10^3}\sqrt{0.0099 \times \frac{34,642}{10^9}}$$

and since the capacity in the primary circuit was the same in both cases:

$$T_{s2} = \frac{2\pi}{10^3}\sqrt{\frac{6 \times 10^6}{10^9}\,C_{s2}} \qquad C_{s2} = \frac{34,642}{23,157}\,C_{s1} = \frac{34,642}{23,157} \times 34.386 = \mathbf{51.44} \text{ cm.}$$

The value of effective capacity of the first 3 meters of wire was therefore $C_{s2} - C_{s1} =$ = 51,44 — 34,386 = **17.054 cm.**

Calling now C_{s3} the capacity of the excited system when 6 meters of wire connected to it we have, since in this case the inductance of the primary was 13 3/4 turns + conn. = = 47,154 cm.

$$C_{s3} = \frac{47,154}{23,157}\,C_{s1} = \frac{47,154}{23,157} \times 34.386 = \mathbf{70.02\ cm.}$$

Hence the value of effective capacity of the second piece of wire 3 meters long was

$$C_{s3} - C_{s2} = 70.02 - 51.44 = \mathbf{18.58\ cm.}$$

Now in the case when 9 meters of wire were attached the inductance of the primary was 16 1/4 turns + conn. = 56,779 cm. Calling C_{s4} the corresponding capacity of the excited system we have:

$$C_{s4} = \frac{56,779}{23,157} \times 34.386 = 84.307 \text{ cm.}$$

Hence effective value of the 3rd piece of 3 meters length was

$$C_{s4} - C_{s3} = 84.307 - 70.02 = 14.287 \text{ cm.}$$

Note* In another series of readings for 9 meters the inductance of primary was found to be 17 turns + conn. = 59,665 cm, and on this basis I find:

$C_{s4}=\frac{59,665}{23,157}\times 34.386=$ **88.597 cm.** According to this the effective value of the 3[rd] piece 3 meters long would then be

$$C_{s4}-C_{s3}=88.597-70.02=\mathbf{18.577}\ \text{cm.}$$

When 12 meters wire were attached the inductance of primary was found to be 19 turns+conn.=67,367 cm. Hence similarly $C_{s5}=\frac{67,367}{23,157}\times 34.386=106.034$ cm, and from this the value of 4[th] piece of wire
$C_{s5}-C_{s4}=100.034-84.307=$ **15.727 cm.** But according to second reading it would be:

$$100.034-88.397=\mathbf{11.437}\ cm, \text{ only.}$$

Finally, when 15 meters were attached the inductance in primary was: 21 1/2 turns+ +conn.=73,142 cm, and therefore: $C_{s6}=\frac{73,142}{23,157}\times 34.386=108.609$ cm. and this would give as value of the last piece of three meters

$$C_{s6}-C_{s5}=108.609-100.034=\mathbf{8.575}\ \text{cm only.}$$

Here possibly inductance of wire begins to assert itself. These values as found are still to be considered.

Colorado Springs

Nov. 18, 1899

Experiments were continued to ascertain influence of elevation upon capacity of a system connected to earth as in previous instances. Coil 344 turns referred to before was again used. Also wire vertical No. 10, 50 feet length and ball 30" diam. The procedure was as in a similar case before. The results were as follows:

Coil without vertical wire.

Capacity in primary	Inductance in primary
$\frac{36}{2}=18$ bottles=0.0162 mfd	$4\frac{13}{16}$ turns+conn.

Coil with vertical wire No. 10, 50 feet.

$\frac{36}{2}=18$ bottles=0.0162 mfd	14 3/4 turns+conn.

Coil with ball 30″ diam. slid on vertical wire.

Capacity primary	Height of ball from center to ground	Inductance in primary
$\frac{36}{2}=18$ bottles$=0.0162$ mfd.	10′ 1″	16 1/4 turns+conn.
,, ,,	33′ 8″	16 7/16 ,, +conn.
,, ,,	57′ 3″	16 5/8 ,, +conn.

On the basis of these readings the following results are obtained: In the first experiment when the wire was attached, the inductance in primary was: $4\frac{13}{16}$ turns+conn.= =14,526 cm. Calling again C_{s1} capacity of excited system we have

$$C_{s1}=\frac{0.0162\times\frac{14,526}{10^9}}{\frac{6\times 10^6}{10^9}}\text{ mfd}$$

$$C_{s1}=\frac{0.0162\times 14,526\times 9\times 10^5}{6\times 10^6}=\mathbf{35,298\ cm.}$$

In the second case with wire 50 long attached to the excited system the capacity of primary being the same as before and the inductance of primary being 14 3/4 turns+ +conn=51,004 cm, we have:

$$C_{s2}=\frac{51,004}{14,526}C_{s1}=\frac{51,004}{14,526}\times 35.298=3.511\times 35.298=123.931\text{ cm.}$$

Hence capacity of wire

$$C_{s2}-C_{s1}=123.93-35.298=\mathbf{88.632\ cm.}$$

Now with ball at its lowest position capacity in primary was as before and inductance 16 1/4 turns+conn.=56,779 cm. Hence

$$C_{s3}=\frac{56,779}{14,526}C_{s1}=3.9088\times 35.298=\mathbf{137.973\ cm.}$$

From this effective value of ball at the height of 10′1″ was

$$C_{s3}-C_{s2}=137.973-123.931=\mathbf{14.042\ cm.}$$

With ball at a height of 33′8″ the inductance in primary was 57,502 cm. and at the height of 57′3″ it was 58,223 cm. As the capacity in primary was the same the values for C_{s4} and C_{s5}, respectively, are at once found since

$$C_{s4}=\frac{57,502}{56,779}C_{s3}\quad\text{and}\quad C_{s5}=\frac{58,223}{56,779}C_{s3}$$

From this we find

$$C_{s4}=1.0127\times 137.973=139.725\text{ cm, and } C_{s5}=1.02543\times 137.973=141.482\text{ cm.}$$

The effective value of capacity of ball at the height

of 33′ 8″ was $C_{s4}—C_{s2}$=139.725—123.931=**15.794 cm**, and

at the height of 57′ 3″ $C_{s5}—C_{s2}$=141.482—123.931=**17.551 cm.**

From these results it would appear that from the lowest to the highest position there was an increase of about 25% total or per foot of elevation 0.53%. These readings were made under conditions not the best.

Colorado Springs

Nov. 19, 1899

In order to further investigate effect of elevation upon the capacity of a system as before a cylinder of thin sheet iron 4″ in diam. was prepared in sections 2 meter long each, there being 7 sections in all. The separate tubes were slipped one into the other so that when one was taken off each time the total length was shortened by exactly two meters. The cylinder was supported vertically above the coil used in the experiments by means of a cord extending from the wooden structure in previous instances described and the experiments were usually begun with the full length of tube and after each adjustment one length was taken off. The results were as follows:

Capacity in primary circuit	Inductance in primary		Length of cylinder
$\frac{2\times 36}{2}$=36 bottles=0.0324 mfd	10 3/4	turns+conn.	14 meters
,, ,, ,,	9 7/8	,, + ,,	12 ,,
,, ,, ,,	8 3/4+1/16	,, + ,,	10 ,,
,, ,, ,,	7 13/16	,, + ,,	8 ,,
,, ,, ,,	6 11/16	,, + ,,	6 ,,
,, ,, ,,	5 5/16	,, + ,,	4 ,,
,, ,, ,,	3 3/4 less 1/32	+ ,,	2 ,,
,, ,, ,,	1 3/8+1/16	,, + ,,	0 ,,

These results are to be calculated.

Note: coil used 344 turns drum 14″ diam. 8 feet length.

Colorado Springs

Nov. 20, 1899

Experiments with coil 344 turns to determine influence of elevation upon capacity of system as before used were repeated.

The results were as follows:

Coil alone

Capacity in primary	Inductance in primary
$\frac{2\times 36}{2}$=36 bottles=0.0324 mfd	1 3/8 turns+conn.

Coil with vertical wire 50 feet (No. 10)

$\frac{2\times 36}{2}$=36 bottles=0.0324 mfd	8 1/16 turns+conn.

Experiments with ball 30" diam.

Capacity primary circuit	Height of ball from center to ground	Inductance primary
$\frac{2\times 36}{2}$=36 bottles=0.0324 mfd	10' 1"	8 7/8+conn.
" " "	33' 8"	9 +conn.
" " "	57' 3"	9 1/8+conn.

from this follows:

When coil was alone the inductance of primary was 1 3/8 turns +conn.=7121 cm. Hence, taking inductance of coil=6×10^6 cm, we have similarly to preceding

$$C_{s1}=\frac{0.0324\times 7121}{6\times 10^6}\text{ mfd} \quad\text{or}\quad C_{s1}=\frac{9\times 10^5\times 0.0324\times 7121}{6\times 10^6}=$$

=**34.61 cm,** slightly less than found before.

Now in second experiment with wire connected to vibrating system the inductance was 8 1/16 turns+conn.=25,472 cm. Since the capacity was the same we have as before

$$C_{s2}=\frac{25{,}472}{7121}C_{s1}=3.577\times 34.61=\mathbf{123.7999\ cm.}$$

From this follows for capacity of wire alone

$$C_{s2}-C_{s1}=123.7999-34.61=\mathbf{89.19\ cm.}$$

When ball was at a height of 10'1" the inductance was 8 7/8 turns+conn.=28,389 cm; in the middle position it was 9 turns+conn.=28,870 cm, and in the highest position it was 9+1/8 turns+conn.=29,351 cm. From this following values are obtained:

$$C_{s3}=\frac{28{,}389}{7121}C_{s1}=\frac{28{,}389}{7121}\times 34.61=3.98666\times 34.61=\mathbf{137.9783\ cm}$$

$$C_{s4}=\frac{28,870}{7121}C_{s1}=4.054\times 34.61=\mathbf{140.301\ cm.}\ \text{and}$$

$$C_{s5}=\frac{29,351}{7121}C_{s1}=4.1218\times 34.61=\mathbf{142.6555\ cm.}$$

The effective capacity of ball at lowest position was

$$C_{s3}—C_{s2}=137.9783—123.7999=14.1784\ \text{cm.}$$

At the middle position it was

$$C_{s4}—C_{s2}=140.301—123.7999=16.5011\ \text{cm.}$$

and at the highest

$$C_{s5}—C_{s2}=142.6555—123.7999=18.8556\ \text{cm.}$$

Hence from lowest to highest there was an increase of about 33% or very nearly an increase of 0.7% per foot or 70% per 100 feet.

Colorado Springs

Nov. 21, 1899

Investigation on influence of elevation upon the capacity continued: The same coil 344 turns on drum of 14" diam., 8 feet long was used. The object was to ascertain the relative capacities of a wire in vertical and horizontal position. A wire No. 14, 10 meters long was experimented with. Results were as follows:

Coil with wire vertical, lowest point being 8' 8" from ground.

Capacity in primary circuit	Inductance in primary
$\frac{22}{2}$=11 bottles=0.0099 mfd	17 1/2 turns+conn.

Coil with same wire horizontal at distance of 8' 8" from ground.

$\frac{22}{2}$=11 bottles=0.0099 mfd	18 turns+conn.

The capacity in exciting circuit was now changed and readings again taken, the results being as follows:

Capacity primary — Inductance primary

Coil with above wire vertical as before

$2\times\frac{36}{2}=36$ bottles$=0.0324$ mfd 6 5/8 turns+conn.

Coil with same wire horizontal as before

$2\times\frac{36}{2}=36$ bottles$=0.0324$ mfd 6 3/4 turns+conn.

Determination of the values of the capacities from preceeding readings:

First set of readings: With wire vertical the inductance in primary circuit was 17 1/2 turns+ +conn.=61,592 cm, and with wire horizontal it was 18 turns+conn.=63,517 cm. Since in all cases before the capacity of the coil alone was found to be approximately 35 cm$=C_{s_1}$ the capacity of the wire in the vertical and horizontal positions was as follows:

Wire in horizontal position:

$$C_{s2}=\frac{0.0099\times 63{,}517}{6\times 10^6}\text{ mfd or } C_{s2}=\frac{0.0891\times 63{,}517}{60}\text{ cm}=\mathbf{94.32\ cm.}$$

and this gives for capacity of wire in horizontal position:

$$C_{s2}-C_{s1}=94.32-35.00=\mathbf{59.32\ cm.}$$

Wire in vertical position $C'_{s2}=\frac{0.0099\times 61{,}592}{6\times 10^6}$ mfd or $\frac{0.0891\times 61{,}592}{60}$ cm=91.464 cm, and this gives capacity of wire in vertical position:

$$C'_{s2}-C_{s1}=91.464-35.00=\mathbf{56.464\ cm}\text{ or a little less.}$$

From second set of readings we get:

Wire vertical: Inductance in primary was 6 5/8 turns+conn.=20,631 cm. Hence

$$C''_{s2}=\frac{0.0324\times 20{,}631}{6\times 10^6}\text{ mfd or }\frac{0.2916\times 20{,}631}{60}\text{ cm}=100.26\text{ cm}$$

and hence value of capacity in this case was for wire alone

$$C''_{s2}-C_{s1}=100.26-35=\mathbf{65.26\ cm.}$$

Wire horizontal: Inductance in primary was 6 3/4 turns+conn.=21,052 cm. Hence

$$C''_{s2}=\frac{0.0324\times 21{,}052}{6\times 10^6}\text{ mfd or }\frac{0.2916\times 21{,}052}{60}\text{ cm}=102.31\text{ cm}$$

and the capacity of the wire in horizontal position was then:

$$C''_{s2}-C_{s1}=102.31-35.000=\mathbf{67.31\ cm.}$$

These readings do not agree as well as they ought to.

To be gone over.

Colorado Springs

Nov. 22, 1899

Measurement of small capacities by resonance method.

This method is suitable to determine capacities too small to be measured in other ways conveniently. Coil with 344 turns before described was again used.
Results:

Coil alone with short piece of stout wire connected to the free terminal.

Capacity in primary circuit	Inductance in primary circuit
$\frac{2 \times 36}{2}=36$ bottles$=0.0324$ mfd	1 1/2 turns+connections

Coil with incandescent lamp 16 c.p. 100 V with two filaments attached to short thick wire

$\frac{2 \times 36}{2}=36$ bottles$=0.0324$ mfd	$1\frac{19}{32}$ turns+conn.

This test gave an idea of the capacity (effective) of the lamp. The primary inductance in first case was 7314 cm. and in the second 7458 cm. from table prepared. From this follows:

$$C_{s1}=\frac{0.0324 \times 7314}{6 \times 10^6}\ \text{mfd or}\ C_{s1}=\frac{0.2916 \times 7314}{60}\ \text{cm}=\mathbf{35.546\ cm.}$$

$$C_{s2}=\frac{0.0324 \times 7458}{6 \times 10^6}\ \text{mfd or}\ C_{s2}=\frac{0.2916 \times 7458}{6 \times 10^6}\ \text{cm}=\mathbf{36.246\ cm.}$$

Here C_{s1} and C_{s2} were respectively the capacities of the system without lamp and with lamp attached. Hence the actual or effective capacity of the lamp in this system was

$$C_{s2}-C_{s1}=36.246-35.546=\mathbf{0.7\ cm.}$$

An approximate idea is also obtained of the capacity of the short piece of stout wire used to attach the small bodies the capacity of which was to be determined. Namely the capacity of the excited system alone being before determined about 35 cm, the capacity of the wire would be

$$35.546-35.000=\mathbf{0.546\ cm.}$$

Colorado Springs

Nov. 23, 1899

Measurement of small capacities by resonance method and mode of determining maximum rise before described by means of diminutive circuit was continued. The coil with 344 turns was again used and in order to get better readings on the self-induction regulating coil in the primary, the primary capacity was reduced. The results were:

1.

Coil with short stout wire alone as before.

Capacity in primary circuit	Inductance in primary circuit
$\frac{36}{2}=18$ bottles$=0.0162$ mfd	$4\frac{13}{16}$ turns+conn.

2.

Coil with lamp same as before.

$\frac{36}{2}=18$ bottles$=0.0162$ mfd	$4\frac{15}{16}$ turns+conn.

3.

Coil with same lamp seal broken

$\frac{36}{2}=18$ bottles$=0.0162$ mfd	$4\frac{31}{32}$ turns+conn.

Note: Curious, the increased capacity probably due to absorption.

4.

Coil with one of my Roentgen tubes as described in articles E.R.

$\frac{36}{2}=18$ bottles$=0.0162$ mfd 5 1/8 turns+conn.

5.

Coil with "double focus tube" target connected.

$\frac{36}{2}=18$ bottles$=0.0162$ mfd 5 1/16 turns+conn.

6.

Coil with same tube one of the electrodes connected.

$\frac{36}{2}=18$ bottles$=0.0162$ mfd 5 3/32 turns+conn.

* **Note:** all of these tubes developed rays fairly strong while tested.

7.

Coil with Lennard tube single terminal as described by me E.R., poorly exhausted, streamers passing through it.

$\frac{36}{2}=18$ bottles$=0.0162$ mfd 5 turns+conn.

From these measurements the capacities can now be found.

Calling the inductances in the primary circuit in each succeeding experiment respectively L_1, L_2, L_3, L_4, L_5, L_6 and L_7 we have with reference to prepared table:

$L_1=4$ 13/16 turns+conn.$=14{,}526$ cm.
$L_2=4$ 15/16 ,, +conn.$=14{,}947$,,
$L_3=4$ 31/32 ,, +conn.$=15{,}053$,,
$L_4=5$ 1/8 ,, +conn.$=15{,}579$,,
$L_5=5$ 1/16 ,, +conn.$=15{,}368$,,
$L_6=5$ 3/32 ,, +conn.$=15{,}473$,,
$L_7=5$,, +conn.$=15{,}158$,,

Calling furthermore the corresponding capacities of the excited system $C_{s1} \dots C_{s7}$ all of them can be at once determined from C_{s1} since

$$C_{s2}=\frac{L_2}{L_1}C_{s1}$$

$$C_{s3}=\frac{L_3}{L_1}C_{s1},\ \text{etc.}$$

Now analogous to previous preceedings of this kind

$$C_{s1}=\frac{0.0162\times L_1}{6\times 10^6}\text{ mfd. or } C_{s1}=\frac{0.0162\times 14{,}526\times 9\times 10^5}{6\times 10^6}=\mathbf{35.298\ cm.}$$

Taking approximately C_{s1}=**35.3 cm** we have:

$$\left.\begin{aligned}
C_{s2}&=\frac{L_2}{L_1}C_{s1}=\frac{14{,}947}{14{,}526}C_{s1}=1.029\times 35.3=36.324\text{ cm}\\
C_{s3}&=\frac{L_3}{L_1}C_{s1}=\frac{15{,}053}{14{,}526}C_{s1}=1.0363\times 35.3=36.58\text{ cm}\\
C_{s4}&=\frac{L_4}{L_1}C_{s1}=\frac{15{,}579}{14{,}526}C_{s1}=1.0725\times 35.3=37.859\text{ cm}\\
C_{s5}&=\frac{L_5}{L_1}C_{s1}=\frac{15{,}368}{14{,}526}C_{s1}=1.058\times 35.3=37.347\text{ cm}\\
C_{s6}&=\frac{L_6}{L_1}C_{s1}=\frac{15{,}473}{14{,}526}C_{s1}=1.0652\times 35.3=37.6\text{ cm}\\
C_{s7}&=\frac{L_7}{L_1}C_{s1}=\frac{15{,}158}{14{,}526}C_{s1}=1.0435\times 35.3=36.8355\text{ cm}
\end{aligned}\right\}\text{from these values follow:}$$

Capacity effective of lamp experiment	$2=C_{s2}-C_{s1}=36.324-35.3=$ **1.024 cm.**
" " seal broken	$3=C_{s3}-C_{s1}=36.58-35.3=$ **1.28 cm.**
" of my Roentgen tube exp.	$4=C_{s4}-C_{s1}=37.859-35.3=$ **2.559 cm.**
" double focus tube target connected	$5=C_{s5}-C_{s1}=37.347-35.3=$ **2.047 cm.**
" " " electrode connected	$6=C_{s6}-C_{s1}=37.6-35.3=$ **2.3 cm.**
" " Lennard tube described	$7=C_{s7}-C_{s1}=36.8355-35.3=$ **1.5355 cm.**

Colorado Springs

Nov. 24, 1899

A test was made with the object of ascertaining how close the table of inductances prepared from measured data agreed with the values determined by resonance method. The procedure was as follows: the coil with 344 turns on drum 14" diam., 8 feet long was again used as suitable for the test and it was excited in the manner before described. In order to establish a different relation between capacity and self-induction of the primary circuit these constants were in each case varied and the adjustment completed until the maximum rise on the terminal or terminals of the excited coil took place. As the period of the system remained in each case the same the products of the capacity and self-inductance in primary remained constant also. Now the capacities in the primary in the succeeding experiments being known or exactly measurable, the various values of inductance in primary were obtained from the relation:

$$L_1 C_1 = L_2 C_2 = L_3 C_3 = \text{etc.}$$

The period of the secondary system was $T_s = \frac{2\pi}{10^3}\sqrt{LC_{s1}}$.

The inductance of coil 344 turns being about 6×10^6 cm. and the average value for C_{s1} from a number of readings with different values of inductance and capacity in primary circuit being 34.9 cm., the period of secondary or excited circuit was thus given.

A reading was now taken at random and resonance was obtained with constants in primary circuit as follows:

Capacity in primary circuit	Inductance in primary
$\frac{36}{2} = 18$ bottles $= 0.0162$ mfd	$4\frac{13}{16}$ turns+conn.

from this the period of primary circuit was:

$T_p = \frac{2\pi}{10^3}\sqrt{0.0162 \times L}$ L being the inductance in primary

Now $T_p = T_s$ or $0.0162 \times \frac{L}{10^9} = \frac{6 \times 10^6}{10^9} \times \frac{34.9}{9 \times 10^5}$ and from this we get L in centimeters:

$$L = \frac{6 \times 10^6 \times 34.9}{9 \times 10^5 \times 0.0162} = \frac{34.9 \times 6}{9 \times 0.0162} = \frac{698}{0.0486} = L = \mathbf{14{,}362\ cm.}$$

by resonance method.

Now from table prepared:

$$\text{Inductance } L = 4\frac{13}{16} + \text{conn.} = \left\{ \begin{array}{lr} \text{Inductance } 4\ 1/2 \text{ turns+conn.} & = 13{,}474 \text{ cm.} \\ \text{Inductance } 5 \text{ turns+conn.} & = 15{,}158 \text{ cm.} \\ \hline \text{Ind. of } 1/2 \text{ turns} & = 1684 \text{ cm.} \\ \text{Ind. of } 1/16 \text{ turns} & = 210.5 \text{ cm.} \end{array} \right.$$

Ind. of 5/16 turn $= 5 \times 210.5 = 1052$ cm approx.

Consequently inductance $L = \text{Ind.} \left\{ \begin{array}{c} 4\ 1/2 + 5/16 \text{ turn} \\ +\text{conn.} \end{array} \right\} = 4\frac{13}{16}$ turn+conn. =

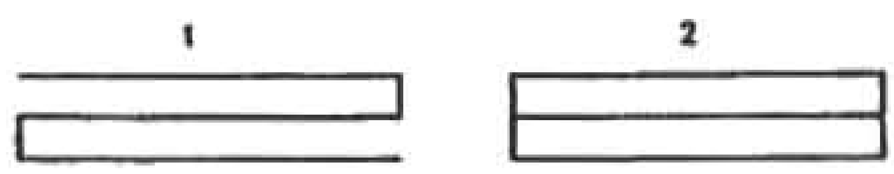
$$= 13{,}474 + 1052 = \mathbf{14{,}526\ cm.}$$

Agreement fairly close, within about 1%. This shows readings are reliable.

Colorado Springs

Nov. 25, 1899

Experiment which follows was made to ascertain how the capacity of the same conductor may be altered by different distribution. The experiment was performed in the following manner. Two lengths of wire No. 10 were taken (rubber covered) and one length was bent zigzag fashion so that a piece with three parallel wires was obtained one meter long. The other length was cut in three pieces 1 meter long each and these were connected at the ends. The difference between the two pieces so prepared will appear



from the sketch in which 1. shows the zigzag wire and 2. the wire cut in three pieces joined in multiple. The distribution in both cases was radically different. These pieces were one after the other placed on the free terminal of a coil with 344 turns and in each case the primary adjusted until resonance was observed. The wires were placed vertically, in the prolongation of the axis of the coil.

An experiment was furthermore made in tuning, not to the real vibration but to a higher harmonic (the next octave) of the primary. The results (with spark gaps slightly changed) were:

Capacity in primary circuit	Inductance primary
$\frac{36}{2}=18=0.0162$ mfd **with wires multiple**	1 1/8 turns+conn.
$\frac{36}{2}=18=0.0162$ mfd **with wire zigzag**	1 1/16 turns+conn.

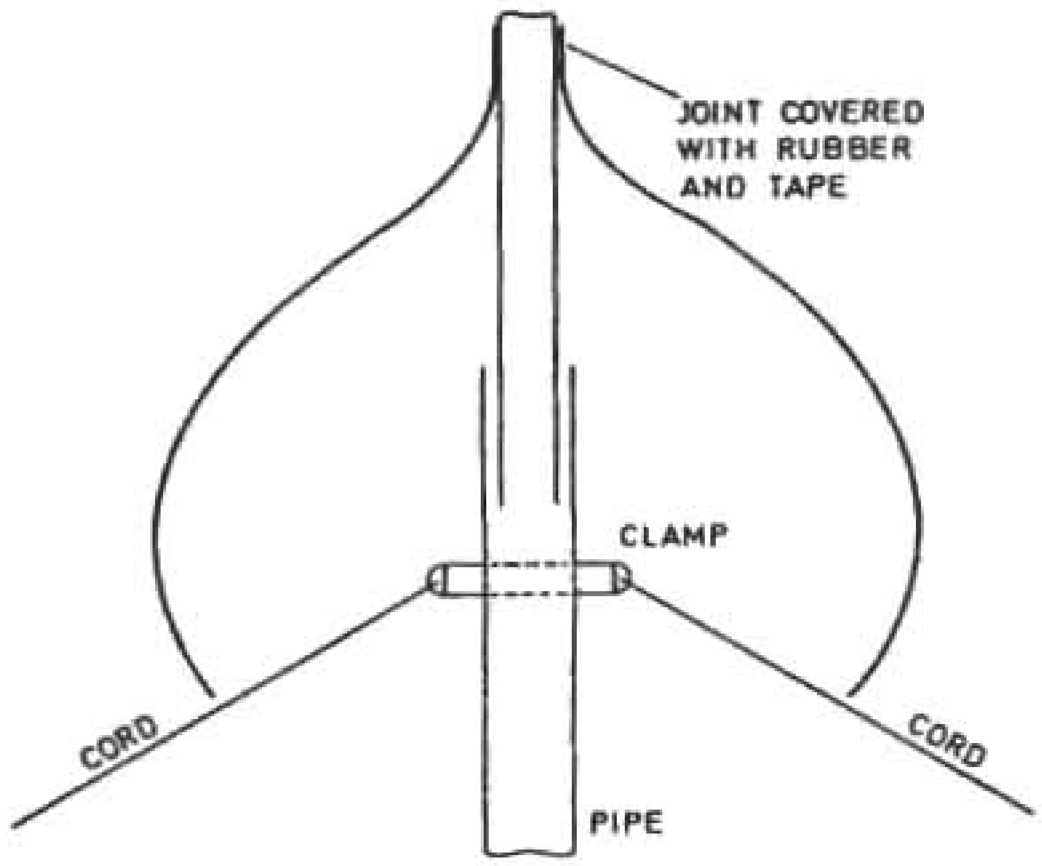
Now the primary inductance in the first case was 6736 cm and in the second case 6635 cm. Hence, the inductance remaining practically the same, the capacity (effective) of the zigzag wire was smaller to the extent of nearly **1.6%**.

Colorado Springs

Nov. 26, 1899

Determination of the capacity of structure of iron pipes by improved method before described.

Note: Originally the structure, to prevent lateral play, was supported sideways by 8 projecting beams at a height of about 80 feet, each beam having fastened into its end a strong champagne bottle. The necks of the bottles abutted against the iron pole and prevented sideways play. They were wrapped with tape to diminish the danger of the necks being broken. This arrangement was good enough and withstood the storm but it did not allow going beyond a certain pressure as the sparks from the iron pipes would jump to the beams which had the bottles fastened into them. To overcome this defect a plan was adopted, contrived long ago, which consisted in providing a conical roof or hood (made in two parts) rounded on the periphery to reduce loss by leakage and fastening four cords under the roof for the purpose of preventing lateral play and steadying this pole. This arrangement is excellent as the sparks can not jump upon and follow the cords to the ground being fastened under the roof where the electrical pressure was extremely



small. The arrangement is indicated in the sketch. The dimensions of the hood were: outside diam. 8 feet., diam. of small circle on periphery 9". The height of the conical surface about 3 1/2 feet. The cords were led to the four corners of the building and fastened to the same by means of a cable of sheet wires over which was slipped a rubber hose with very thick wall and which was wrapped around three glass insulaters supported on the pole on each corner. It was thought of advantage to insulate the ropes thoroughly and for this purpose they were soaked about a week in linseed oil boiled out and dried in the sun afterward. The cords went down at an angle such that the nearest point of the hood was two feet distant. This arrangement permitted the charging of the pole easily up to a million volts. This is the best arrangement I have found so far for supporting a body to be charged to so high a potential as is necessary for instance in the transmission of messages over great distances. It has been in use since a few weeks ago but the measurements of capacity of the structure before recorded were made without the hood. Presently the readings were taken with the hood with following results:

Coil 344 turns drum 14" with iron structure connected to free terminal.

Capacity in primary circuit	Inductance in primary circuit
$\frac{2\times 36+12}{2}=\frac{84}{2}=42$ bottles$=0.0378$ mfd	21 1/8 turns+conn.

Coil with connecting wire alone shifted away from structure (4 feet).

$\frac{2\times 36+12}{2}=42$ bottles$=0.0378$ mfd	4 turns+conn.

From this follows: the inductance in primary circuit in the first case was 75,548 cm; in the second case 12,319 cm referring to table of inductances before used. Hence capacity of excited system in first

$$C_{s1} = \frac{0.0378 \times 75{,}548}{6 \times 10^6} \text{ mfd, or } \frac{0.3402 \times 75{,}548}{60} \text{ cm} = C_{s1}$$

And similarly $C_{s2} = \dfrac{0.3402 \times 12{,}319}{60}$ cm, C_{s2} being capacity of excited system in second experiment. This gives for actual or effective capacity of **structure with hood**

$$C_{s1} - C_{s2} = \frac{0.3402}{60}(75{,}548 - 12{,}319) \text{ cm} = \frac{0.3402}{60} \times 63{,}229 \text{ cm} = \mathbf{358.5 \text{ cm.}}$$

* Small corrections for inductance may have to be taken later.

Effective capacity of structure of iron pipes with new hood again determined by resonance method. The new "extra coil" was used, its inductance being as before 0.02 H. The readings were as follows:

Capacity in primary	Inductance in primary
Coil with structure and connecting wire	
5×36—12=168 bottles=0.1512 mfd	20 3/8 turns+conn.
Coil with connecting wire alone placed at 4 ft. distance	
4×36=144 bottles=0.1296 mfd	7 turns+conn.
other readings:	
50 bottles=0.045 mfd	17 1/4 turns+conn
40 ,, =0.036 mfd	20 turns+conn.
38 ,, =0.0342 mfd	20 3/4 turns+conn.
39 ,, =0.0351 mfd	(approx) 20 3/8 turns+conn.

From these readings follows:

Inductance in first case, with structure, in primary was 20 3/8 turn+conn.=72,661 cm.
Inductance in second case, without structure, in primary was 7 turn+conn.=21,894 cm.

Calling C_{s1} and C_{s2} the effective capacities of the excited system in the two cases respectively, we have:

$$C_{s1} = \frac{0.1512 \times 72{,}661}{2 \times 10^7} \text{ mfd, and } C_{s2} = \frac{0.1296 \times 21{,}894}{2 \times 10^7} \text{ mfd, hence}$$

$$C_{s1} - C_{s2} = \frac{0.1512 \times 72{,}661 - 0.1296 \times 21{,}894}{2 \times 10^7} =$$

$$= \frac{10{,}986.3432 - 2837.4624}{2 \times 10^7} = \frac{8148.88C8}{2 \times 10^7} \text{ mfd,}$$

or

$$\frac{9 \times 8148.8808}{2 \times 10^2} \text{ cm} = \mathbf{366.7 \text{ cm.}}$$

effective capacity of structure **with hood.**

Capacity of structure without hood before found with extra coil was 311.2 cm, hence for hood alone we get 366.7—311.2=**55.5 cm.** From first and last reading it appears that the secondary capacities in the two cases were as $\frac{168}{39}$. Now the capacity of excited system in last reading was

$$C'_{s2}=\frac{0.0351\times 72{,}661}{2\times 10^7}\ \text{mfd, or}\ C'_{s2}=144.77\ \text{cm.}$$

From this would follow value

$$C'_{s1}=\frac{168}{39}\times 114.77=494.39\ \text{cm.}$$

Hence $$C'_{s1}-C'_{s2}=494.39-114.77=\mathbf{379.62\ cm.}$$

This value does not agree quite closely with that before found but the tuning was not quite exact in last case.

Note: It now seems that the tuning in all previous cases when structure was determined was made to the first octave instead of to the fundamental tone. **This is to be ascertained.** If this be so then capacity would be much greater.

Colorado Springs Notes

Dec. 1—31, 1899

To be completed:

Dec. 11, 12, 13 Application for Page for separation of gaseous mixtures by high tension discharge of oscillator.

Dec. 17 Description of phenomenon on Pike's Peak in the few days of eclipse of moon.

Patent note

Increase of capacity uses in the arts and scientific measurements.

Colorado Springs Nov. 10. 1899.

is barely visible when the slide $\perp$ is on the point giving the maximum rise on the exciting system. By a little experience it becomes easy to thus locate the maximum within 1/10 of one per cent. By resorting to ordinary experimental resources it is practicable to reach greater precision still. Of course the greater the resonance of the exciting system the better it is. There are various instruments or detectors of all kinds which allow the method to be refined to any degree desired. A very simple improvement, effective and readily at hand is however to provide a source of energy for bringing the filament or wire just to a point when its luminosity can be detected by the observer. I connect the lamp to a battery of constant e.m.f. through the choking coils graduating the heat of the latter so that the filament is brought preliminarily to the required temperature. A small amount of surplus energy supplied from the secondary loop is then sufficient to make the filament bright. Thus, less energy is taken from the exciting system and the location of the maximum is readier and more easy. Diagram below illustrates this arrangement as it is separate from the high frequency current which can not of course pass through the choking coils. The method will be very suitable for having circuits for many purposes as in telegraphy.

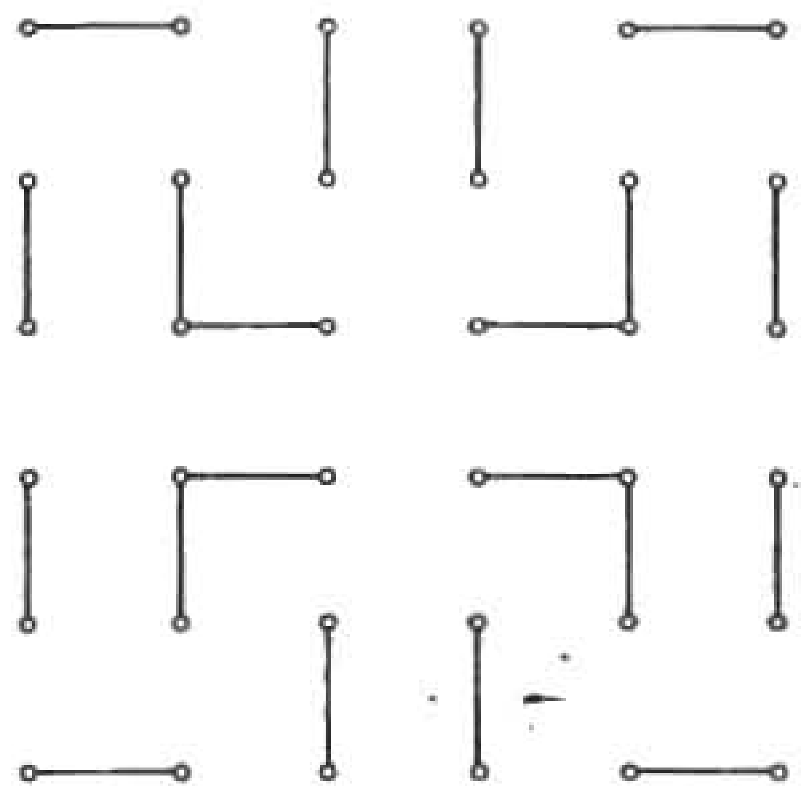
In the former experiments the coil before described: 1314 turns wire No. 18 on drum 14" diam. 8 feet long was used the object

Colorado Springs

Dec. 1, 1899

Some particulars about the *apparatus* used in the *experiments here.*

The connections of the bottles in the two tanks frequently referred to as the "old tanks", to which the primary cables and the regulating coil were usually connected and by means of which the finer adjustments of capacity in the primary circuit were made, are as shown in the sketch. The top brass plate has 16 plugs disposed at equal distances in a square and the 36 bottles in the tank being connected by copper springs as indicated, each plug enabled the cutting out or in of two bottles, with the exception of the four central plugs which cut in or out three bottles each. Thus the smallest variation of the capacity on one side was one bottle or 0.0009 mfd, approx. But with the tanks in two sets in series as usually employed it was one half of one bottle. Considering the large number of bottles the variation was small enough for most purposes. The bottles in the new tanks were divided in three sets, twelve bottles in each.



Measured length of all connections on the *condenser sets in primary:*

From top of right condenser to break	$2'\ 5\frac{1''}{2} = 29.5''$
Through break wheel and sp. rod	$2'\ 4\frac{1''}{2} = 28.5''$
From back to regulating coil..................................	$3'\ 10'' = 46''$
Up through second break and rod	$1'\ 10'' = 22''$
Connection to left condenser	$3'\ 7'' = 43''$
To bottom of left condenser	$1'\ 8\frac{1''}{2} = 20.5''$
Connection on bottom between condensers	$3'\ 6'' = 42''$
Up to top of right condenser	$1'\ 8\frac{1''}{2} = 20.5''$

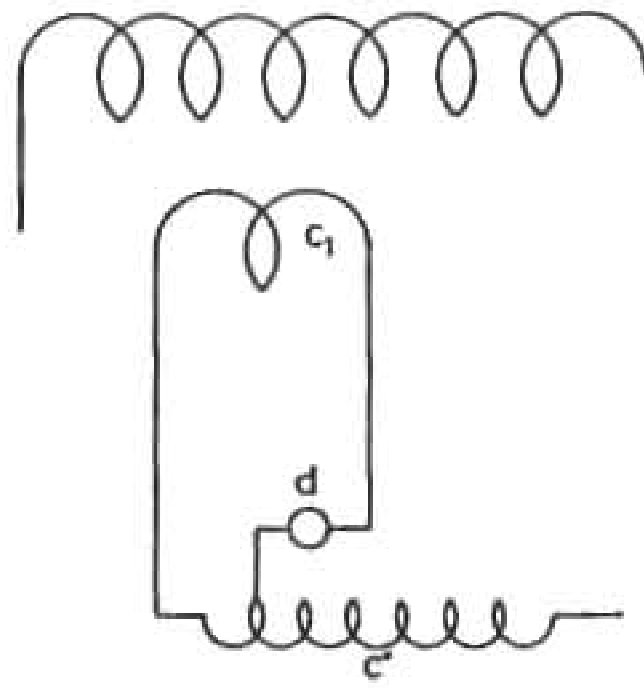
Total length of connections is thus $252'' = 641$ cm, nearly or 21 feet. The section of the connections is partially that equal to the cable used in primary 1 cm radius and partially less. The inductance determined by resonance analysis is about *5000 cm total.* The calculated value a trifle more.

Dec. 2, 1899

Various ways of tuning circuits or *determining the maximum of resonant rise.*

In the course of the experiments conducted here a number of such ways have been resorted to most of which have been described or at least referred to, but it may be useful to record here once more those which have been found most satisfactory. They are diagramatically illustrated in Figs. 1—5. below:

1.



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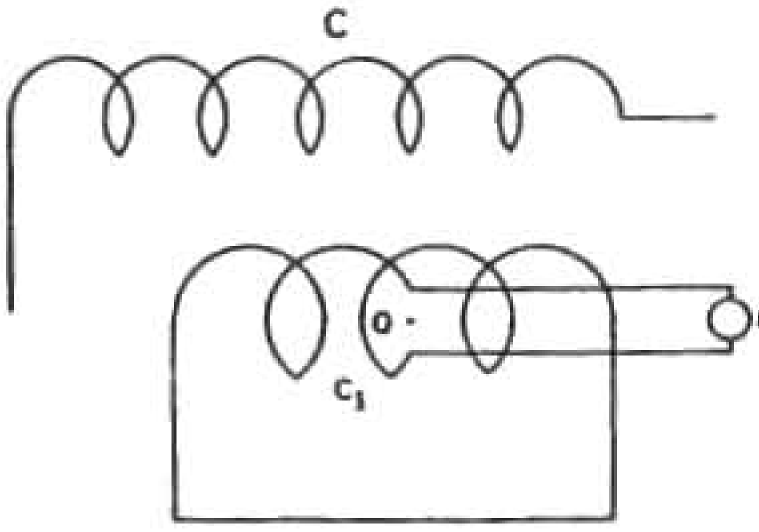

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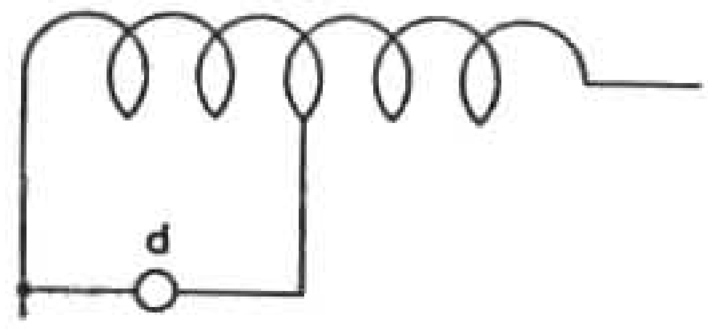
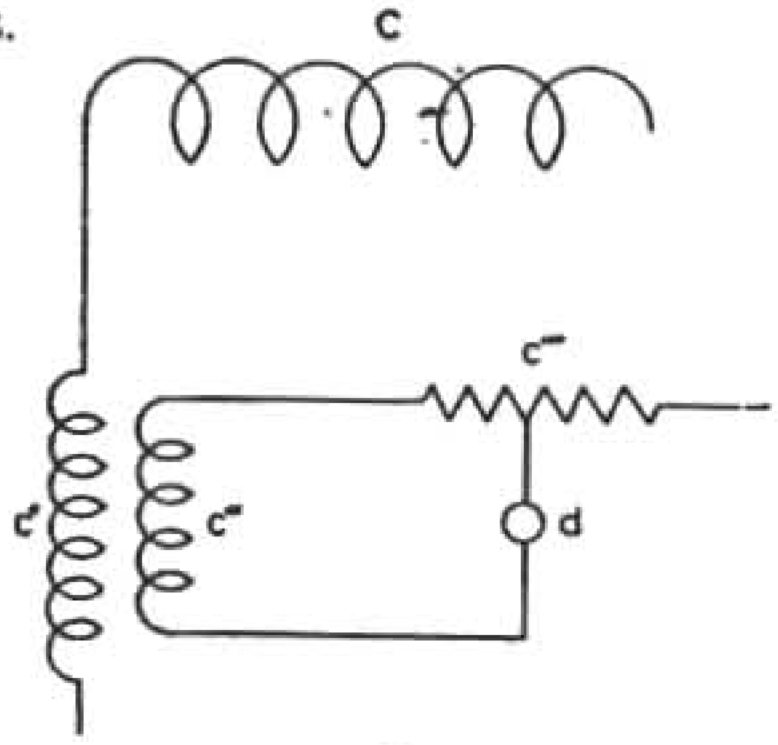
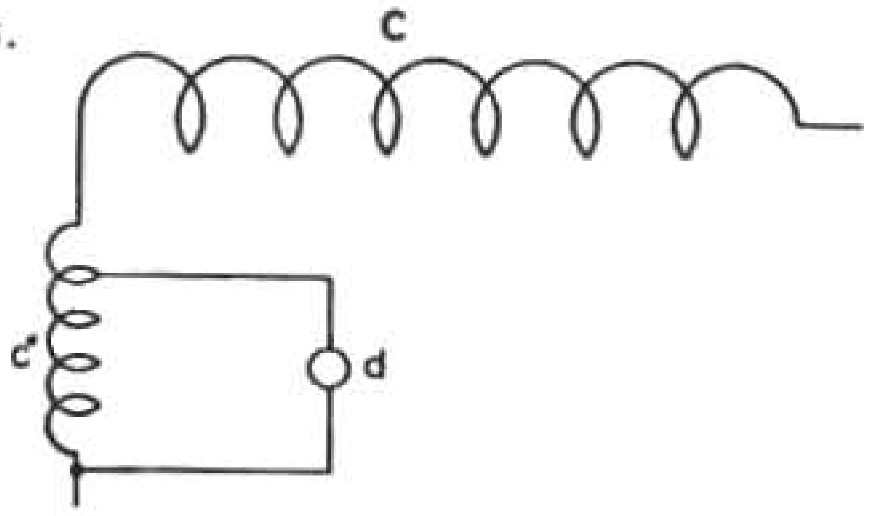


4.



5.



In arrangement illustrated in Fig. 1. a small circuit c_1, in very loose inductive connection with the resonating circuit C, is used to detect the maximum. This small circuit c_1 which exercises no appreciable reaction upon circuit C contains another coil c'' or else a resistance which is noninductive for the purpose of adjusting the effect to suit the indicating device d which is most generally a microscopic spark gap, vacuum tube or any hot wire instrument, as a minute lamp specially made to suit the purpose, a Cardew voltmeter or any other instrument. In Fig. 2. the adjustment of the effect upon d is effected by turning the circuit around a point o or else by approaching small circuit c_1 to or receding with same from circuit C. In Fig. 3. a number of turns of the resonating circuit C are spanned by device d, this number being adjustable. In Fig. 4. again a small coil c'' in series with coil C is placed inductively in connection with a small circuit c''' which again may be adjustable in the manner shown or in any other way. Finally in Fig. 5. a small coil c'' in series with C is spanned by device d. Coil c'' has its turns adjustable. *This method seems best.*

Colorado Springs

Dec. 3, 1899

Determination of free vibration of *new "extra coil". No. 10 wire* wound on frame 8′ 3″ diam. and 8′ length modified by taking off five turns on top and placing the last five turns two grooves apart instead of one groove as the rest of turns. In this modification there are just 100 turns in the coil. The excitation was effected from the secondary the connection being made to a point *o* 3/4 turns from the ground plate as indicated in the

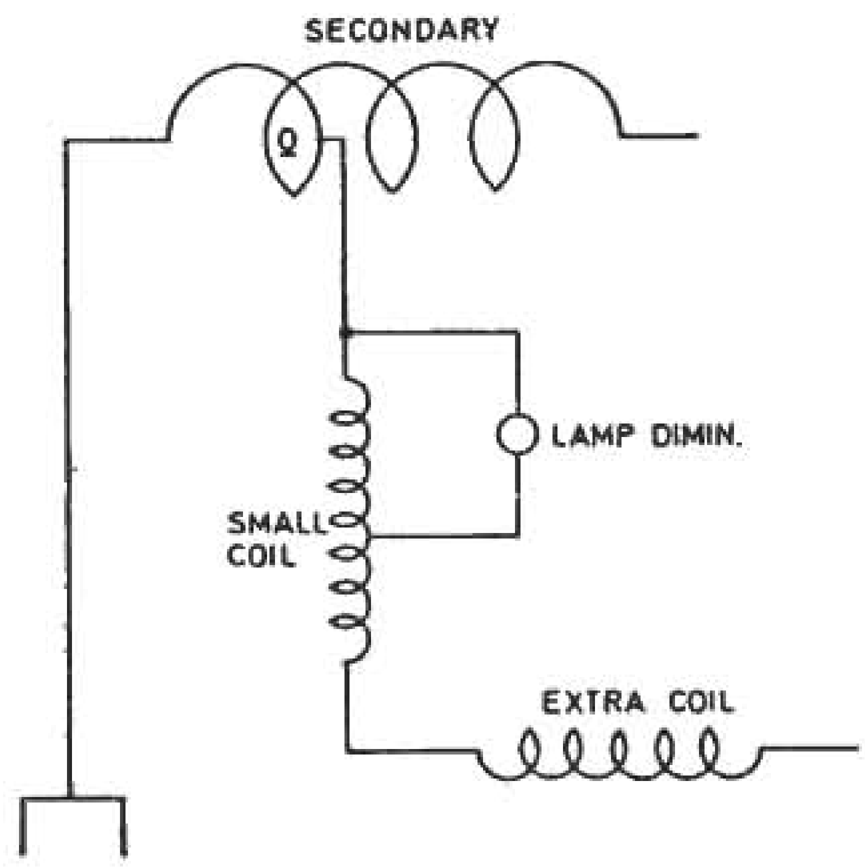


diagram. The maximum rise was determined by means of a diminutive lamp shunting a few turns of an adjustable small coil in series with the extra coil, the small coil being of an inductance entirely negligible as compared with that of the extra coil. The readings for resonating condition were as follows:

Capacity in the primary or exciting circuit	Inductance in the pr. or exc. circuit
$\frac{2 \times 36}{2}$=36 bottles=0.0324 mfd	16 1/16 turns regulating coil+1 primary turn, that is two primary cables in multiple *as modified by reaction of secondary.*
$\frac{4 \times 36}{2}$=72 bottles=0.0648 mfd	5 5/8 turns of coil+primary as above.

From first reading, taking the inductance of primary turn as modified by the secondary 41,000 cm, the period of the oscillation was $T_1 = \frac{2\pi}{10^3}\sqrt{0.0324\,L}$, L the inductance of primary being that of primary turn+16 1/16 of regul. coil=41,000+56,000=97,000 cm. This gives

$$T_1 = \frac{2\pi}{10^3}\sqrt{0.0324 \times \frac{97}{10^6}} = \frac{2\pi}{10^6}\sqrt{0.0324 \times 97} =$$

$$\frac{2\pi}{10^6} \times 1.773 = \frac{11.13444}{10^6} \text{ and } \mathbf{n = 90{,}000 \text{ nearly.}}$$

From second reading, the inductance of 5 5/8 turns of regulating coil being 17,300 cm and total inductance of primary 41,000+17,300=58,300 cm. We have the period

$$T_2=\frac{2\pi}{10^3}\sqrt{0.0648\times\frac{583}{10^7}}=\frac{2\pi}{10^6}\sqrt{0.0648\times 58.3}=$$

$$=\frac{6.28\times 1.944}{10^6}=\frac{12.2}{10^6}\text{ and } \mathbf{n=82{,}000 \text{ approx.}}$$

Note: The tuning was very sharp in both cases, but in the second case the secondary reaction *was smaller*, i.e., inductance of the primary greater.

Colorado Springs

Dec. 4, 1899

Experiments to *establish equivalence* between *the inductance of the primary loop* comprising two primary cables in multiple (*with secondary reacting*) and *that of turns of the regulating coil* in primary circuit.

Resonance analysis was resorted to and the coil of 344 turns on drum 14" diam. 8 ft. long, wire No. 10 was again used. The coil employed had a very small regulating coil in series, and a minute lamp placed across the few turns of this latter coil was employed to ascertain the maximum resonant rise in the coil excited. The results were as follows:

Capacity in the primary circuit	Inductance in the primary circuit
	1.
8 jars on each side, that is 4 jars= =0.0036 mfd	One primary loop as above+6 3/4 turns reg. coil.
	• Small coil in series with coil of 344 turns had 9 turns in circuit *entirely negligible.*
	2.
Capacity same as above	15 1/4 turns regulating p. coil *only*
	• Small coil had 22 turns inserted, still entirely negligible against 344 turns coil

Since resonance was obtained in both cases and the primary capacity in both tests remained the same we have the primary inductances in both cases equal and from this follows that *under the conditions* of these tests the inductance of the primary *as modified* by the *secondary* was equivalent to 15 1/4—6 3/4 turns of the primary regulating coil. Now from the table of inductances the value for the 15 1/4 turns is 52,930 cm and that for the 6 3/4 turns, inserted in the first case, is 21,052 cm. Hence the inductance of primary cables in this instance was

$$L_p=52{,}930-21{,}052=\mathbf{31{,}878}\ \mathbf{cm.}$$

Thus the secondary, though "open", diminished in this case the primary inductance from 56,400 cm to the above value or about 43.48%.

Colorado Springs

Dec. 5, 1899

Experiments to ascertain *equivalence of inductance of primary loop* (two primary cables in multiple) with *secondary reacting*, and *inductance* of *turns of regulating primary coil* under modified conditions.

Again the coil with 344 turns was used and the maximum resonant rise in same determined in the manner described before. A greater capacity was used this time in the primary so as to come closer to the free vibration of the secondary and thus cause a stronger reaction upon the primary loop. The conditions for resonance were satisfied with the following values:

1.

Capacity in primary circuit	Inductance in primary circuit
$\frac{2\times 36}{2}=36$ bottles$=0.0324$ mfd	21 3/4 turns pr. regulating coil *only*

2.

Capacity in primary circuit	Inductance in primary circuit
$\frac{2\times 36}{2}=36$ bottles$=0.0324$ mfd	one primary loop as above+15 1/2 turns reg. coil.

Since in both tests the primary capacity was not changed in the least the inductance of the primary loop in this instance was equivalent to that of 21 3/4 turns, less that of 15 1/2 turns of the regulating coil in the primary. This means the inductance of the primary loop was equivalent to that of $21.75-15.5=6.25$ turns of the primary regulating coil or it was $6.25\times 3850=$ **24,063 cm** only. Induct. diminished 57.33%. This is a still smaller value than found yesterday but is very probably near the maximum as the secondary showed evidence of a resonating condition. These experiments show the danger of allowing for the amount of secondary reaction. This is to be borne in mind.

Colorado Springs

Dec. 6, 1899

Further experiments to ascertain *equivalence of inductance of the primary loop* (two primary cables in multiple) with *secondary reacting*, and that of *turns of primary regulating coil* under conditions again modified.

In the present tests the "new extra coil" modified so as to have only 100 turns was used (this is to be explained). The coil was used exactly as that of 344 turns before and the maximum rise was determined in the same way and by the same means as in preceding cases. The results of the two comparative tests were as follows:

1.

Capacity in the primary circuit	Inductance in primary circuit
$\frac{5\times 36-24}{2}=\frac{156}{2}=78$ bottles $=0.0702$ mfd	11 5/16 turns of primary regul. coil *only*

2.

Capacity in primary circuit	Inductance in primary circuit
same as above $=0.0702$ mfd	one primary turn $+3$ 1/2 turns reg. pr. coil.

From these tests it follows that under present conditions the inductance of the primary loop with secondary reacting was equivalent to that of 11 5/16 turns less that of 3 1/2 turns of the primary regulating coil. Now the table of inductance gives inductance of the 11 5/16 turns $=37{,}775$ cm, and that of the 3 1/2 turns $=11{,}164$ cm. Hence the inductance of the primary loop under these conditions was

$$L_p=37{,}775-11{,}164=\mathbf{26{,}611}\text{ cm.}$$

The secondary was resonating to some extent but not as well as in experiments recorded yesterday. The diminution of inductance due to secondary reaction was here 52.82 %.

Note: These tests make it advisable to break the secondary on *more* points when the primary is used for inductance.

Colorado Springs

Dec. 7, 1899

Experiments to ascertain to what extent *induced currents in the ground* might affect the *primary and secondary oscillating systems* now used in the laboratory.

Resonance analysis was resorted to and the experiments were performed in the following manner: a *square* frame 11′ 1/4″ each side and 3 3/4″ high, wound with 14 turns wire No. 10 was supported horizontally above the ground, its elevation above the latter being made adjustable. This coil was tuned in various positions and the effect of the ground observed on the change of the period of oscillation in the various positions. In order however to get a better range of reading and also to reduce as much as practicable the effects of the distributed capacity in the coil wound on the square frame the same was joined in series with another coil of 344 turns wound on a 14″ diameter drum, which was before used, but so that the coil on the square frame was between the ground connection and the coil of 344 turns, this for the purpose of maintaining between the turns of the square coil a comparatively small difference of potential thus reducing the effect of distributed capacity of the same. By using the additional coil the vibration was rendered slower and a better range of reading was secured. The two coils were excited in the manner repeatedly referred to and described, the maximum resonant rise being determined by means of a minute lamp shunting a few adjustable turns of a very small coil of entirely negligible inductance which was in series with both the coils used.

The results of the tests are indicated in the following table:

Capacity in primary exciting circuit	Distance of square coil from ground	Inductance in primary circuit
1. $\frac{4\times 36}{2}$=72 bottles=0.0648 mfd	1′ 3″+0	4 1/4 less 1/32 turn reg. pr. coil
2. „ „	1′ 3″+2′	4 1/16 turns reg. pr. coil
3. „ „	1′ 3″+4′	4 less 1/32 „
4. „ „	1′ 3″+6′	3 7/8+1/32 „

It is to be stated by way of explanation that the *floor* was 1′ 3″ above ground. A simple inspection of the above results shows that induced currents do not prominently assert themselves. This might have been expected considering the extreme dryness of the ground which, as before pointed out, made it too difficult at the outset of these experiments to get a good ground connection. But it is evident from the above table that the electrostatic capacity is an important element. This is quite evident since the vibration of the system comprising the square coil is *quickened by elevation* of the frame. If there were *induced currents* generated in the ground it would *be just the opposite*. Since the capacity in the primary exciting circuit remained the same in all four experiments the capacity of the excited circuit, the inductance of which remained the same, was varied exactly as the inductance of the primary circuit. Now with reference to the table of inductances the inductances in experiments 1, 2, 3, and 4, respectively, were: 12,824, 12,463, 12,247 and 12,103 cm. The increase of distance from 1 to 2 was 160%; from 2 to 3 61.5%; from 3 to 4 38.2%. Putting results together we have:

Increase of distance		Amount of the diminution of capacity
2'	160%	361
2'	61.5%	216
2'	38.2%	144

The numbers indicate a general proportionality but now the capacity of the excited system should be known.

This will be followed up.

* Capacity of primary cables with reference to earth should be determined.

Colorado Springs

Dec. 8, 1899

In response to note from I. Hawthorne forwarded to "Northamerican" Philadelphia, dispatch as follows:

"In response to a request from friend I. Hawthorne the following statement:

"Confining myself to my chosen sphere, I believe that the mastery of electrical forces was as great and beneficial an achievement as the Century has witnessed. As to the immediate future my thoughts are dominated by two ideas, one of which is already realized, while the other is on the eve of accomplishment. The art of governing the movements and performances of distant automatons, enabling machines to act as creatures endowed with a mind, will demonstrate to the leading nations the futility of armaments and impracticability of the present life destroying implements of war and will lead to more permanent peaceful relations, in harmony with the humanitarian spirit and enlightenment of the age; while the art of transmitting electrical energy through the natural media, without the use of leading wires, over vast distances, from great centers, as Niagara, will open up inexhaustible resourses of wealth and power and, by rendering immense amounts of the energy of the sun available to the wants of man, will perhaps make it possible for him to produce similar wonderful changes and transformations on the surface of our globe as are, to all evidence, now being wrought by intelligent beings on a neighbouring planet."

N. Tesla

Experiment to determine the inductance of coil wound on the *square frame* before used by means of resonance analysis and *another known coil:*

The square coil was connected in series with coil of 344 turns as before and maximum rise was determined in the same way as described in preceding experiments. The resonant condition was obtained with

Coil 344 turns in series with square coil

Capacity in primary or exciting circuit

$\frac{36}{2}$=18 bottles=0.0162 mfd

Inductance in primary circuit:

5 less 1/32 turns reg. coil=15,000 cm approx.

With coil 344 turns alone

$\frac{36}{2}$=0.0162 mfd

15 less 1/16 turns reg. coil=51,700 cm

Assuming now that the addition of capacity when coil on square frame is connected in series be negligible, as will be the case when the coil which is to be measured is very small in comparison to the other we may assume, since the capacity in the primary circuit was the same in both experiments, that the inductances in the primary or exciting circuit are as the inductances of the excited circuit in both the successive tests. Calling inductance of square coil L and remembering that inductance of the coil with 344 turns was before recorded to be 0.006 henry, we have:

$$\frac{L+0.006}{0.006}=\frac{51{,}700}{15{,}000}=\frac{517}{150} \text{ and } \frac{517}{150}\times 0.006-0.006=L=$$

$$=0.006\times\left(\frac{517}{150}-1\right)=0.006\times\frac{367}{150}=L=\mathbf{0.01468\ henry.}$$

The correctness of this estimate is of course based on the assumption that the capacity added to the excited system by the square coil is very small compared with the total capacity.

Colorado Springs

Dec. 9, 1899

Results obtained Dec. 7, with square coil in various positions reconsidered.

The results referred to indicate that the induced currents generated in the ground are of little or no moment but that the capacity owing to nearness of ground may be of great importance. To get a better idea of the variation of the capacity and also to settle any doubt as to the influence of the induced currents it is necessary to estimate the capacity of the system which was excited. For the present purpose it is thought the consideration of the "ideal" capacity of the coils will lead to results not far from the truth. Now on a previous occasion the "ideal" capacity of a coil with 344 turns was found to be 34.6 cm. Since this "ideal" capacity increases with the square of the length of the turns, owing to the fact that it increases with the energy stored in simple proportion, and the energy again in proportion to the square of the difference of pressure between each two adjacent turns, the difference of pressure is simply proportionate to the length. Now the length of one turn on square coil is $4\times 11'\ 1/4''=4\times 132.5''=530''$. The coil of 344 turns being wound on a drum 14" diam., the length of each of its turns is $3.1416\times 14''=44''$ nearly. The "ideal" capacity of the square coil will therefore be, considering also turns, $\frac{14}{344}\times\left(\frac{530}{44}\right)^2\times$ ideal cap. of coil 344 turns $=\left(\frac{265}{22}\right)^2\times\frac{14}{344}\times 34.6=145.1\times 1.4=203.14$ cm. Hence total "ideal" capacity will be the *sum* of these, that is approximately **238 cm.** This value obtained at a given height above ground being known, we can now calculate the increments of capacity, or decrements of same as the coil is approached to or removed from the ground and it ought to be found that these increments or decrements are proportionate to the distances of coil from ground in the successive positions of the coil. I think that it is unnecessary to go through the trouble at present because it is very probably so.

Note: Such proportionality would be destroyed if there would be any appreciable currents generated in the ground.

Colorado Springs

Dec. 10, 1899

Estimate of turns of "Extra coil" to be used *with the structure* of iron pipes as *capacity on free terminal.*

In a previous test resonance was obtained with new extra coil and elevated structure as capacity with

Capacity in primary exciting circuit	Inductance in primary circuit
168 bottles=0.1512 mfd	20 3/8 turns reg. coil

In this test the extra coil had 105 turns. The turns being now reduced to 100, the inductance of the coil will be smaller by a ratio of $\left(\frac{100}{105}\right)^2=0.907$. Hence instead of 20,000,000 cm as before, the inductance of the coil will be 20×0.907 million cm or 18,140,000 cm=0.018 henry approx. Had the above test been performed with the coil so modified, the capacity in the primary exciting circuit — assuming the inductance the same — would have been smaller by a ratio of $\frac{18.14}{20}$ or we would have had instead of 168 bottles about $\frac{18.14}{20}\times 168=153$ bottles approximately$=0.0009\times 153=0.13759$ mfd capacity. We have therefore as basis for computation:

Extra coil with structure: 1.

Capacity-primary: 0.13759 mfd — Inductance-primary: 20 3/8 turns reg. coil.+conn.

Now in another test of extra coil but without structure results were

Extra coil alone: 2.

Capacity-primary: 0.0648 mfd — Inductance-primary: 5 5/8 turns reg. coil.+conn.

These data enable us to determine how many turns are to be left off on bottom of coil in order that it be in resonance with the primary exciting system under the *best working conditions of the latter;* the structure being connected to the coil.

Now the secondary, to be at best, should work with all jars available and the regulating coil should be *all cut out* in the primary. This is namely the condition corresponding to full output and highest economy. Under such working conditions the secondary will modify greatly the inductance of the primary and for the present approximate estimate it will be close enough to assume a diminution of about 50% of the primary inductance so that the latter may be put at 28,000 cm. This would then give in Test 2:

Extra coil alone

Capacity-primary	Inductance-primary
0.0648 mfd	28,000+5 5/8 turns reg. coil+conn= =28,000+17,263=45,300 cm. approx.

But capacity in primary with *all jars* as would be required *for best working* would be $\frac{8 \times 36}{2}$ =144 bottles=0.1296 mfd. Reduced to this capacity the inductance in primary would have been in reading 2. instead of 45,300 cm only $\frac{0.0648}{0.1296} \times 45{,}300 =$ **22,650 cm.**

Taking now reading 1. when structure was connected to the free terminal of coil the inductance in primary was 20 3/8 turns+conn.=72,660 cm from table. But in this case the capacity was 0.13759 mfd. Reducing this to the capacity when secondary works best, that is, to 0.1296 mfd the inductance with this capacity would have been larger by a ratio of $\frac{0.13759}{0.1296} = 1.048$ or it would have been $72{,}660 \times 1.048 = 76{,}150$ cm, approx. Thus we have the following data:

Extra coil with structure connected: a)

Capacity in primary 0.1296 mfd — Inductance in primary =76,150 cm and

Extra coil alone without structure: b)

Capacity in primary 0.1296 mfd — Inductance in primary 22,650 cm.

Now to secure resonance with structure attached and under best working conditions of the exciting system with possibly only a very few turns of the regulating coil in primary, we have from above to reduce inductance of extra coil by a ratio of $\frac{22,650}{76,150}$. For same length turns will be

$$\sqrt{\frac{2265}{7615}} \times 100 = 54\text{—}55 \text{ t.}$$

Colorado Springs

Dec. 14, 1899

Test to ascertain free vibration of new "Extra Coil System" (latest)

The new "extra coil" latest type is wound on same frame 8′ 3″ diam. and 8 feet in length, the wire being this time No. 6 instead of wire No. 10 as before. There are presently just 100 turns. A coil of No. 6 wire wound on drum 14″ diam. and 8 feet long, which was used repeatedly before, was connected in series with this latest extra coil and resonance determined by means of the adjustable small inductance as usual and a miniature lamp shunting the turns. The results with *no* capacity on the terminal which was "free" were:

Capacity in primary circuit	Inductance in primary circuit
$\frac{5 \times 36}{2} = \frac{180}{2} = 90$ bottles $= 0.081$ mfd	One primary turn (two cables in multiple)+ +3 turns regul. coil

When a ball 30″ diam. with 4 feet of wire was connected to the free terminal the readings were:

Capacity-primary: 0.081 mfd	Inductance-primary: as above, only 7 1/2 turns in regul. coil.

In both cases the excitation was effected through the secondary of the oscillator from a point of the same 3/4 turns from ground plate. In the first case the inductance of primary, taking into consideration the secondary reaction, is estimated at 41,000 cm. Adding to this the inductance of connections and 3 turns of regulating coil=10,000 cm the total inductance was about 51,000 cm. This with a capacity of 0.081 mfd would give the period of the system comprising the two coils in series

$$T_1 = \frac{2\pi}{10^3}\sqrt{0.081 \times \frac{51}{10^6}} = \frac{2\pi}{10^6} \times 2.03 = \frac{12.75}{10^6} \text{ approx. and } n = 78{,}500$$

approx. per second. When the capacity of a ball of 30″ diam. is associated with the system we have the inductance of the primary circuit, as before, 41,000 cm for the primary turn with secondary reacting plus 7 1/2 turns regulating coil and connections=23,580 cm, with reference to the table, that is, total=64,580 cm. The period in the second case was therefore

$$T_2 = \frac{2\pi}{10^3}\sqrt{0.081 \times \frac{6458}{10^8}} = \frac{2\pi}{10^7}\sqrt{523.098} = \frac{6.28 \times 22.9}{10^7} = \frac{143.8}{10^7}$$

and n=70,000 approx. The coil connected in series with the extra coil was wound on a drum used before. In one case this drum was wound with wire No. 10, 346 turns and in this case it had an inductance of 6,040,000 cm. The new "extra coil" latest having 18,000,000 cm approximately, the total inductance may be placed closely enough at 18,000,000+ $+\left(\frac{283}{346}\right)^2 \times 6,000,000$ cm, the coil in series with the extra coil here used having 283 turns. This gives inductance total 18,000,000+4,000,000 approx.=22,000,000 cm. Now if the latter coil of 283 turns would have been omitted then the system would have vibrated quicker in proportion

$$\sqrt{\frac{22 \times 10^6}{18 \times 10^6}} = \sqrt{\frac{22}{18}} = \frac{\sqrt{11}}{3} = 1.106$$

times or since n in the first case was=78,500, the* extra coil alone will vibrate $1.106 \times 78,500$=86,800 approx. If the inductance in primary be left the same as in the first case then the number of bottles will be reduced by a ratio of $\frac{18}{22} = \frac{9}{11}$ or instead of 90 bottles total we shall want $\frac{90 \times 9}{11} = \frac{810}{11}$=74 bottles or nearly so; this means 148 bottles on each side or about 4 tanks. This is only an approximate estimate for first guidance. Perhaps the reaction of the secondary is somewhat overestimated in this case as it was not resonating in these tests or near the resonating condition.

* With figures taken from second test the results are very nearly the same.

Colorado Springs

Dec. 15, 1899

List, for future reference, of some coils used in the experiments up to present.

Coil	wound on drum	25.25"	diam.	cord No. 20	404 turns	Length of this drum 71 1/2" appr.
Coil	,,		,,	cord No. 10	259 ,,	
Coil	,,		,,	wire No. 10	274 ,,	
Coil	,,	24"	diam.	wire No. 6	207 ,,	70 3/4" long
Coil	,,	10 5/16	,,	Bell wire No.18	550 ,,	
Coil	,,	14"	,,	cord No. 10	346 ,,	Length of this drum 8 feet appr.
Coil	,,	14"	,,	Bell wire No.18	1314 ,,	
Coil	,,	14"	,,	No. 6 wire	283 ,,	
Coil	,,	5"	,,	No. 2 ,,	91 ,,	38 1/4" long
Coil	,,	5"	,,	No. 6 ,,	129 ,,	38 3/4" ,,
Coil	,,	4"	,,	No. 10 ,,	185 ,,	4 ft. long.
Coil	,,	4"	,,	No. 10 ,,	141 ,,	3 ft. ,,
Coil	,,	30 1/2"	,,	No. 25 ,,	132 1/2 turns	

* Exp. resonance

Coil on drum	26" diam.		
	upright stand	No. 6 wire	136 turns
Coil on spool	12" diam.	2 1/8" long	28 layers Bell wire No. 18

$$\text{turns} \begin{Bmatrix} \text{to } 20 \text{ lay. } 28 \\ \text{,, } 28 \text{ lay. } 27 \end{Bmatrix} = 20\times 28+8\times 27=560+216=776 \text{ turns}$$

• Exp. to determine periods of vibration.

New extra coil as first wound 8′ 3″ diam., 8 ft. long, 105 turns No. 6 wire, between grooves 1/2″. A number of these coils have been before described and their inductances measured. Since the same drums were repeatedly wound with different wires it is easy to determine the inductances on the bases of data before recorded with some of them. It is proposed to make later a complete table of the coils with the inductances and other particulars worked out.

Colorado Springs

Dec. 16, 1899

In carrying on some experiments to ascertain the effects of induction from the primary circuit of the oscillator in the laboratory, at a distance from the same, a square frame described on a previous occasion was used. This frame was 11′ 1/4″=132.5″==336.55 cm long and as much wide and 3 3/4″=9.525 cm deep. It was wound with 14 turns of wire No. 10. To ascertain the period of vibration of this coil a formula before arrived at and frequently used was again employed. This formula applies to coils of circular cross section but it was thought that the results would be close enough also for the square coil with due allowances. To apply the rule the square surface was converted into a circular one equal to it and the diameter of the latter was calculated. Finally an allowance was made for the diminished length of the wire on the circular coil for the same number of turns. Calling D the diameter of the circle we have $\frac{D^2\pi}{4}=336.55^2$ from which follows $D=380$ cm. approximately. The formula referred to is

$$p=\frac{3\times 10^{10}\sqrt{(\tau+d)\tau}}{D^2 N\sqrt{\pi^3 K}\sqrt{d}}$$

Here τ=distance of wires=0.46 cm; d=diam. of wire=0.254 cm;

$$(\tau+d)=0.714;\quad \sqrt{\tau(\tau+d)}=0.573;$$

K as found$=\frac{52}{10^6}$; $\sqrt{d}=0.5$; N= number of turns=14; p=natural frequency of coil to be found.

This gives in the present case:

$$p=\frac{3\times 10^{10}\times 0.573}{3.1416\times 380^2\times 14\times\sqrt{\frac{3.1416\times 52}{10^6}}\times 0.5}=$$

$$=\frac{6\times 10^{10}\times 573}{3.1416\times 144{,}400\times 14\times\sqrt{3.1416\times 52}}=\frac{6\times 10^{8}\times 573}{44\times 1444\times\sqrt{3.1416\times 52}}=$$

$$=\frac{3438\times 10^{8}}{44\times 1444\times 12.8}=\frac{3438\times 10^{8}}{813{,}300}=\frac{3438\times 10^{6}}{8133}=423{,}000 \text{ approximately}$$

$$\text{and } n=\frac{423{,}000}{2\pi}=67{,}360 \text{ nearly.}$$

This would be for a cylindrical coil of 14 turns, but the turns of the square coil are longer and, since the inductance is proportionate to the square of the length of wire, and the frequency again proportionate to the square root of the inductance, n will be smaller in proportion $\frac{4\times 336.55}{3.1416\times 380}=\frac{1193}{1346}$ or the system will vibrate about $\frac{1193}{1346}\times 67{,}360$ or roughly 60,000 per sec. The *experiments showed* it vibrated *nearly this number* of times.

Colorado Springs

Dec. 31, 1899

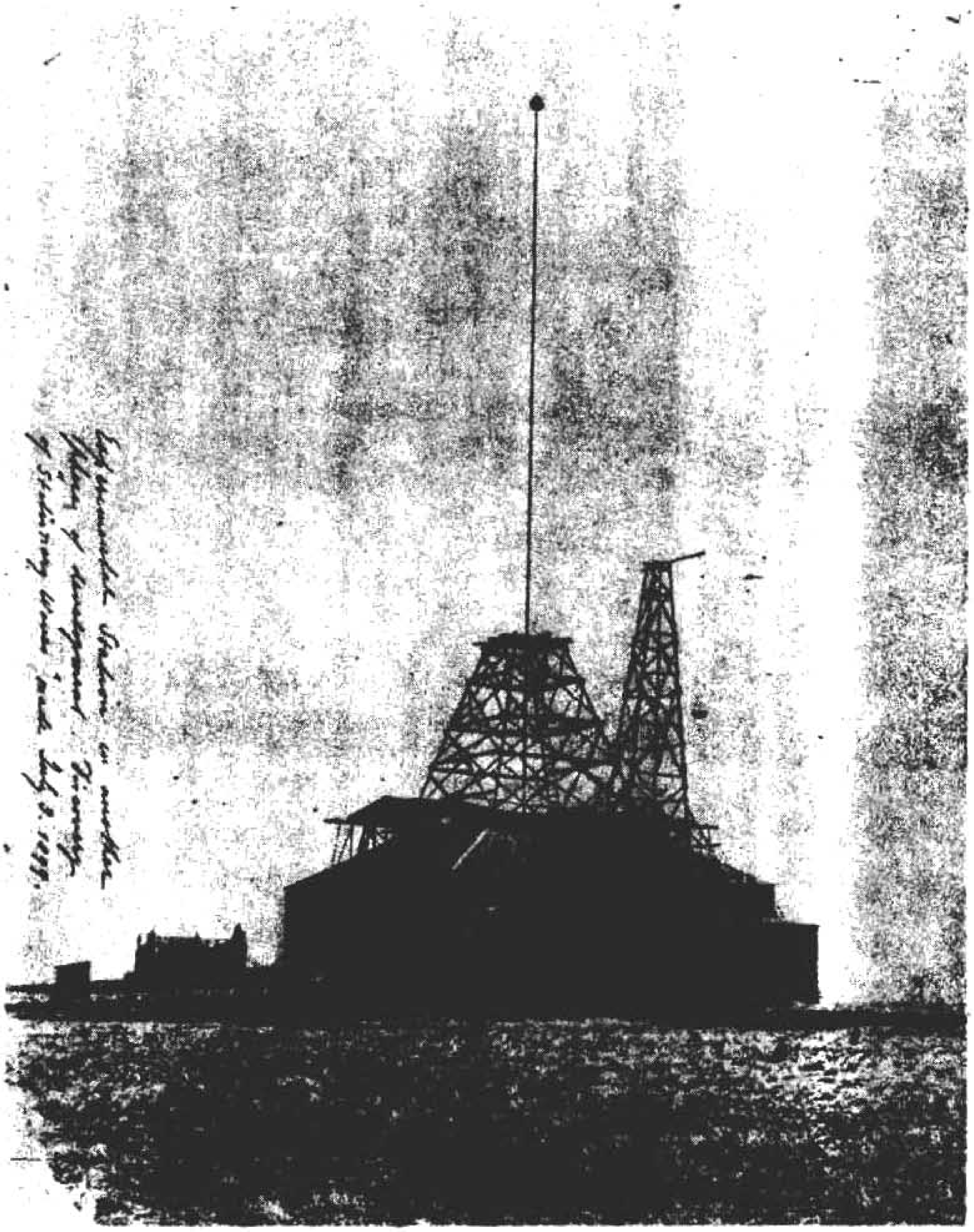
Of the photographs taken here from Dec. 17 to Dec. 31, 1899 by Mr. Alley the following were forwarded through him to my friends of the Century:

I. Front view of laboratory from Pike's Peak side. Isochromatic 11"×14" plate. Time — afternoon before sunset. This is a very fine photograph showing well the advantage of the pure atmosphere here. Such sharpness of outlines and amount of detail could not be obtained in New York, for instance. I conclude that the high quality of photographs obtainable in these parts is not so much due to the skill of the professionals as to the pure atmosphere and abundance of light.

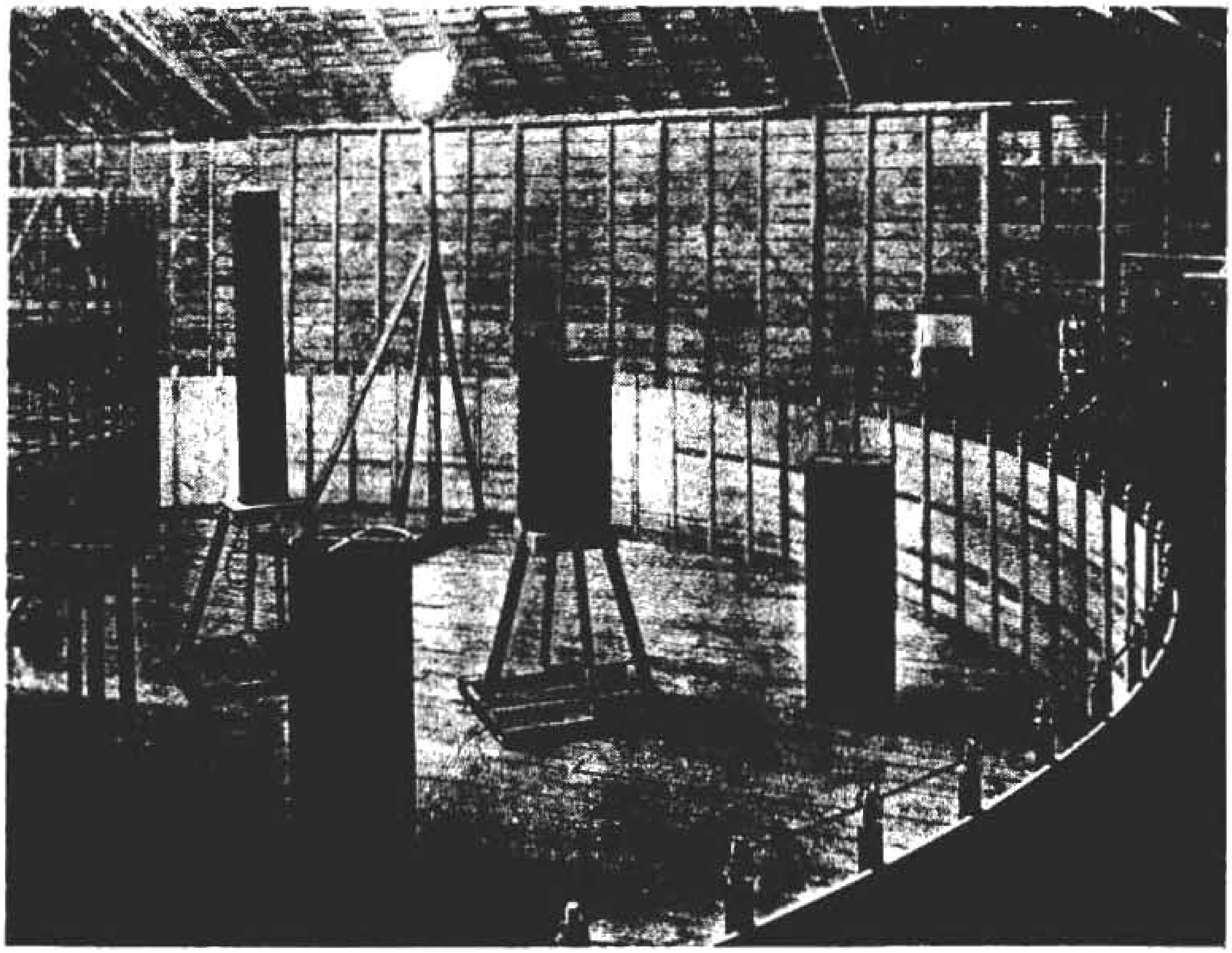
II. View of interior showing half of circle of oscillator frame with several coils grouped inside; Westinghouse transformer, lightning arresters in background, also part of central "extra coil" latest pattern and a 30" ball on stand. The photograph was taken late in the afternoon. Light was rather feebly diffused. The plate was as before, 11"×14" isochromatic.

III. View of interior, chiefly showing condensers, break motor and regulating coil in primary of oscillator. Westinghouse high tension transformer and supply transformers in background, also arresters. Plate same as before, the photograph was taken at the same time, practically as that described under II. The diffused daylight was very feeble. Both of these plates are excellent.

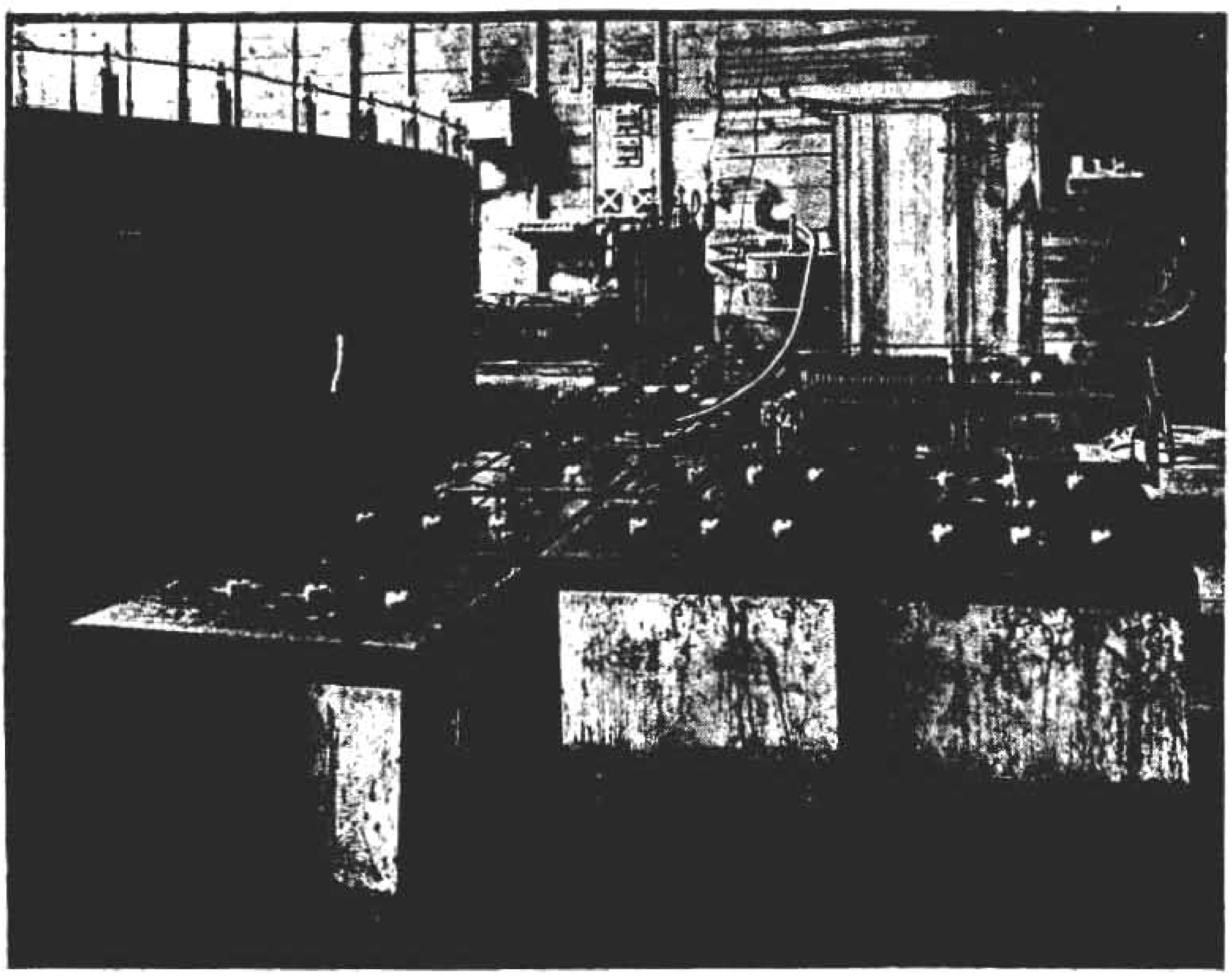
IV. View of laboratory from the rear by moonlight; *1 h 20 min.* exposure. Moon about 2/3 full. Showing Pike's Peak Range and all details of building very sharply. Such photographs by moonlight could be secured only in a few places. Plate same as before, 11"×14" isochromatic.



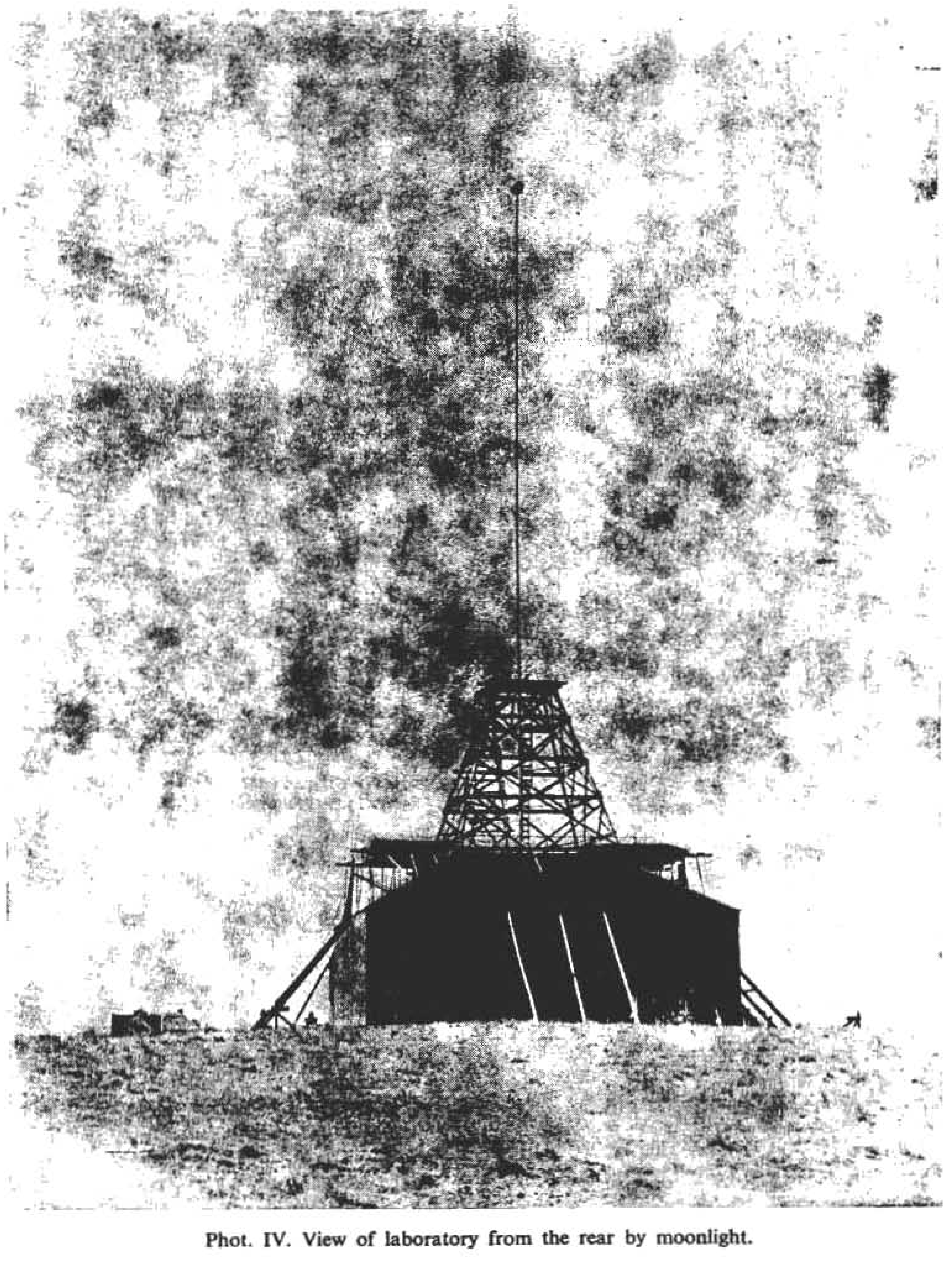
Phot. I. Front view of Laboratory from Pike's Peak side.



Phot. II. View of interior showing half of circle of oscillator frame with several coils inside.

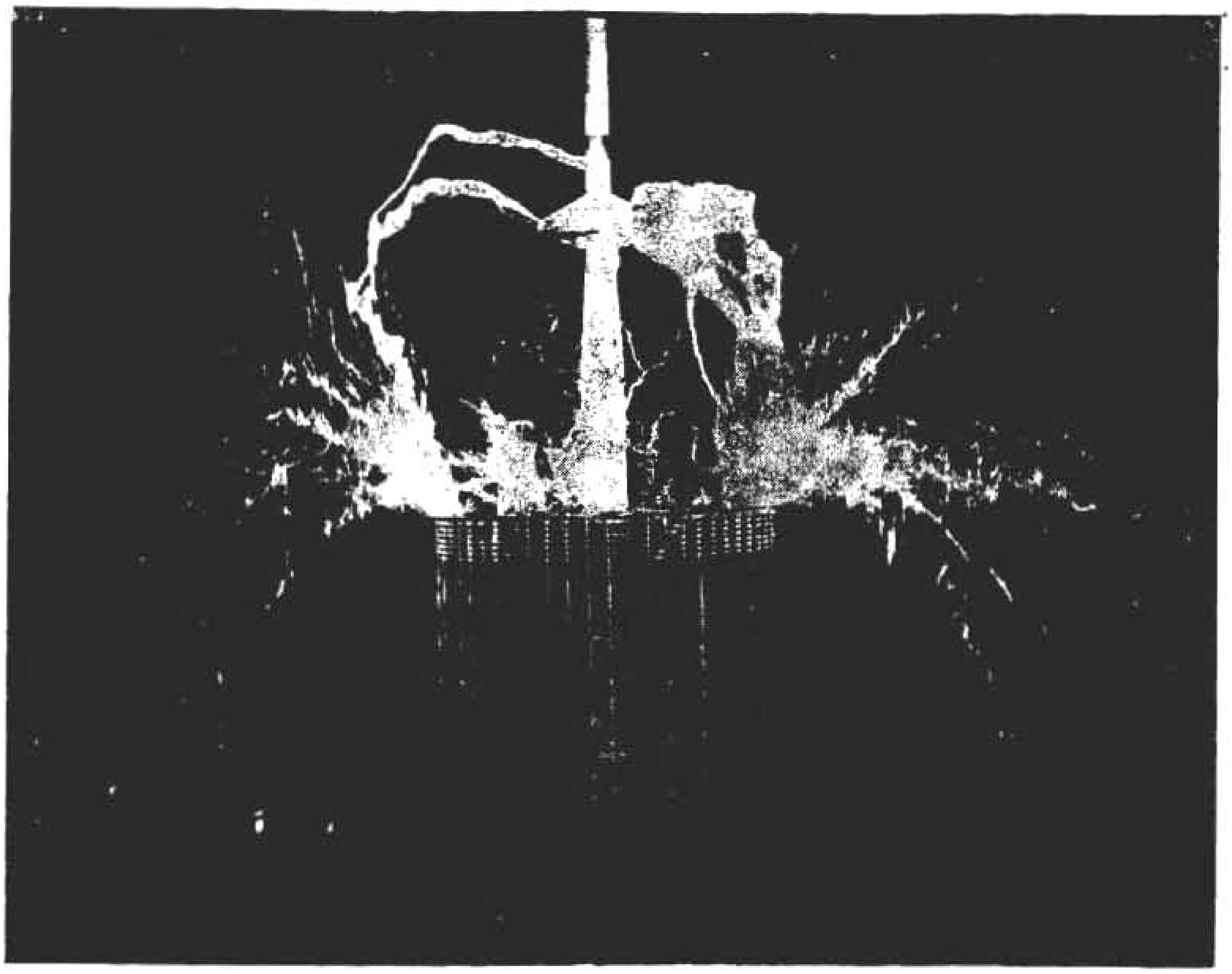


Phot. III. View of interior, chiefly showing condensers, break motor and regulating coil in primary of oscillator. Westinghouse high tension transformer, supply transformers and arresters in background.

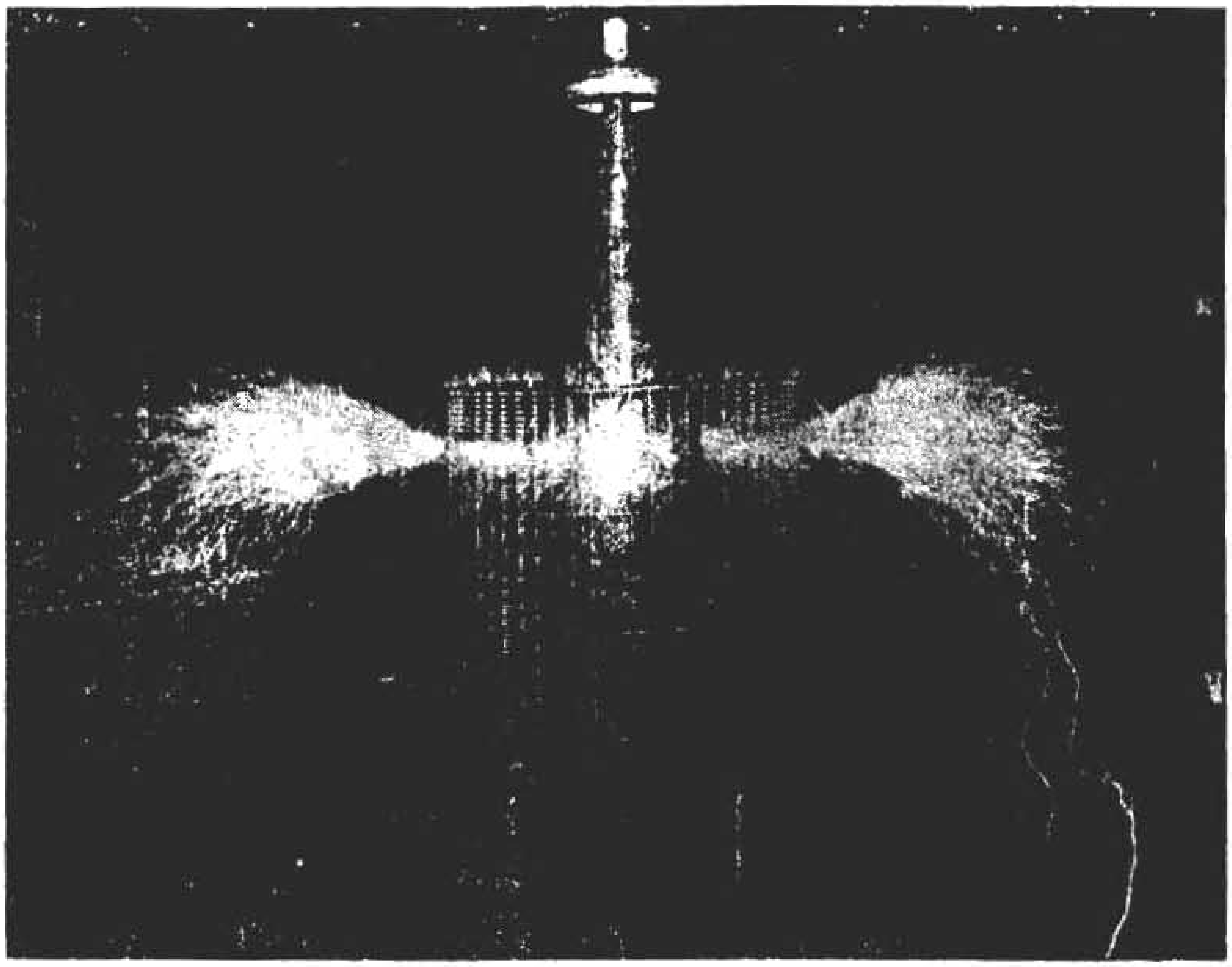


Phot. IV. View of laboratory from the rear by moonlight.

Phot. V. View of interior showing a number of coils differently attuned and responding to vibration transmitted to them from an electrical oscillator[41].



Phot. VI. Normally excited "extra coil".



Phot. VII. View of "extra coil" in action.

V. View of interior much the same as in II. The secondary and various coils placed inside, particularly the central "extra coil", are resonating. The latter is connected to a point of the first secondary turn about 3/4 turns from ground connection, nevertheless the streamers are powerful. Other coils are connected to the same point while a ball 30" on a stand and a coil on a stand are connected to the last turn of secondary. Strong sparks were passing from top to bottom of extra coil and the secondary last turn shows strong streamers. About 100 short flashes or throws of switch and afterwards an exposure of 15 minutes to ordinary arc lamp placed in corner of building for the purpose of photography. The arc light is much preferable to flash light as the time can be closely determined in each case. The isochromatic plate is *decidedly better*. In this plate there is a red dye used in coloring the plate, otherwise it is the same as the Cramer "Crown". The plate used was "instantaneous Cramer isochromatic", same size as those before. This observation suggests a line of experiment which might lead to useful results. It would consist in using plates each dyed with a different color to bring out specific effects. The vibrations of the system was the normal or nearly so as recorded in previous notes.

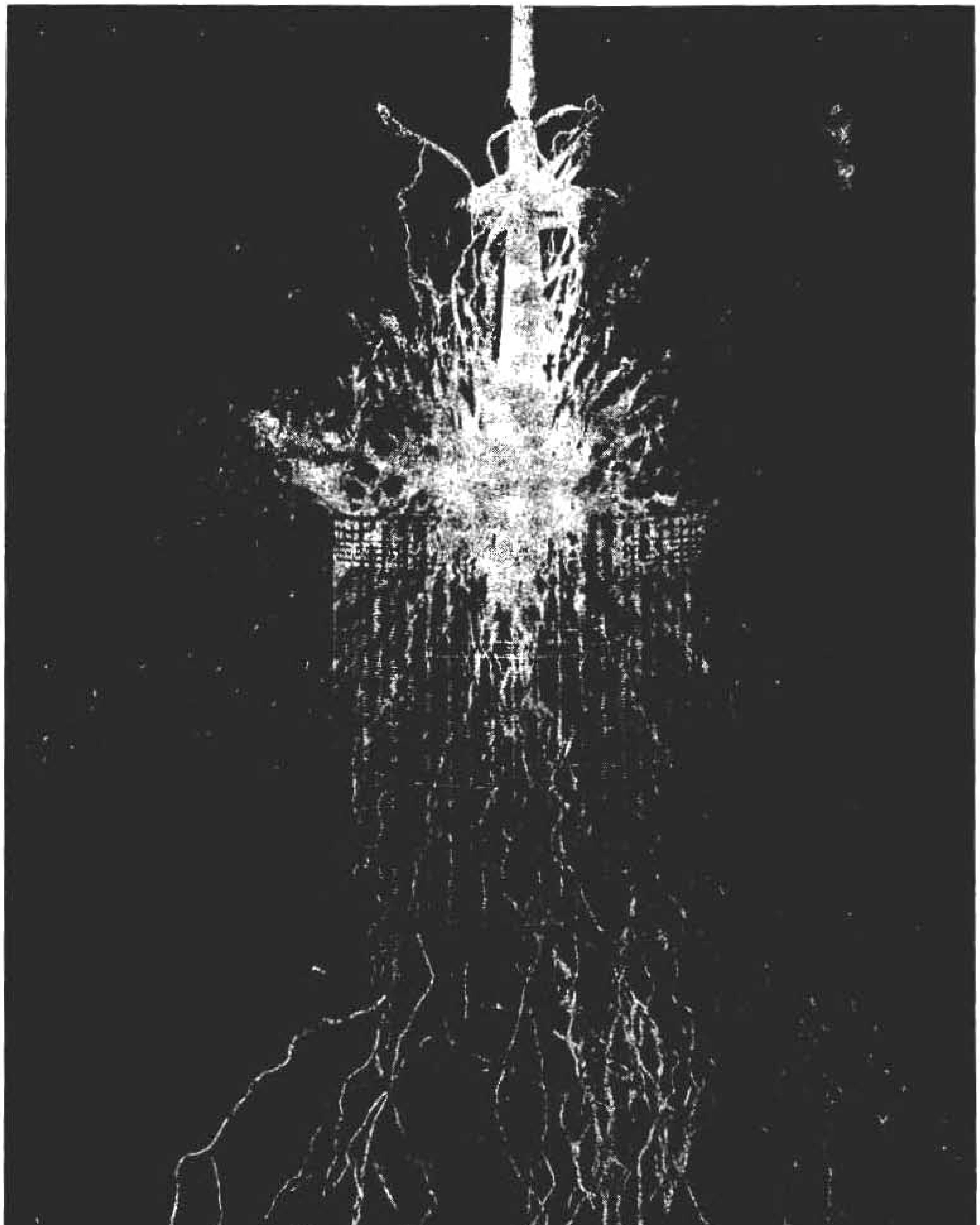
VI. View of "extra coil" excited as normally. A bare brass ring formed of tube 3/4" diam. is placed on top. The switch is thrown in once and held about 3 seconds. The roof has been slightly opened and also the door in front to create a draught. The effect of the latter is noted easily on the separation of the individual discharges. This feature is particularly noticeable on sparks passing to the hood carried by the structure of iron pipes repeatedly described. These sparks pass in curious ways preferring frequently a long path to a short one. This is peculiar to these discharges of high tension emanating from a single free terminal. Some streamers are broken in places to continue stronger afterwards. From end to end of the longest streamers about 50—55 feet in a *straight* line. This photograph is extremely beautiful on account of the character as well as arrangement of the streamers. The extra coil is excited as normally but not quite full power. The vibration is as previously recorded.

The same kind of plate as before was used and the exposure to arc light was 15 minutes, about half light cut off.

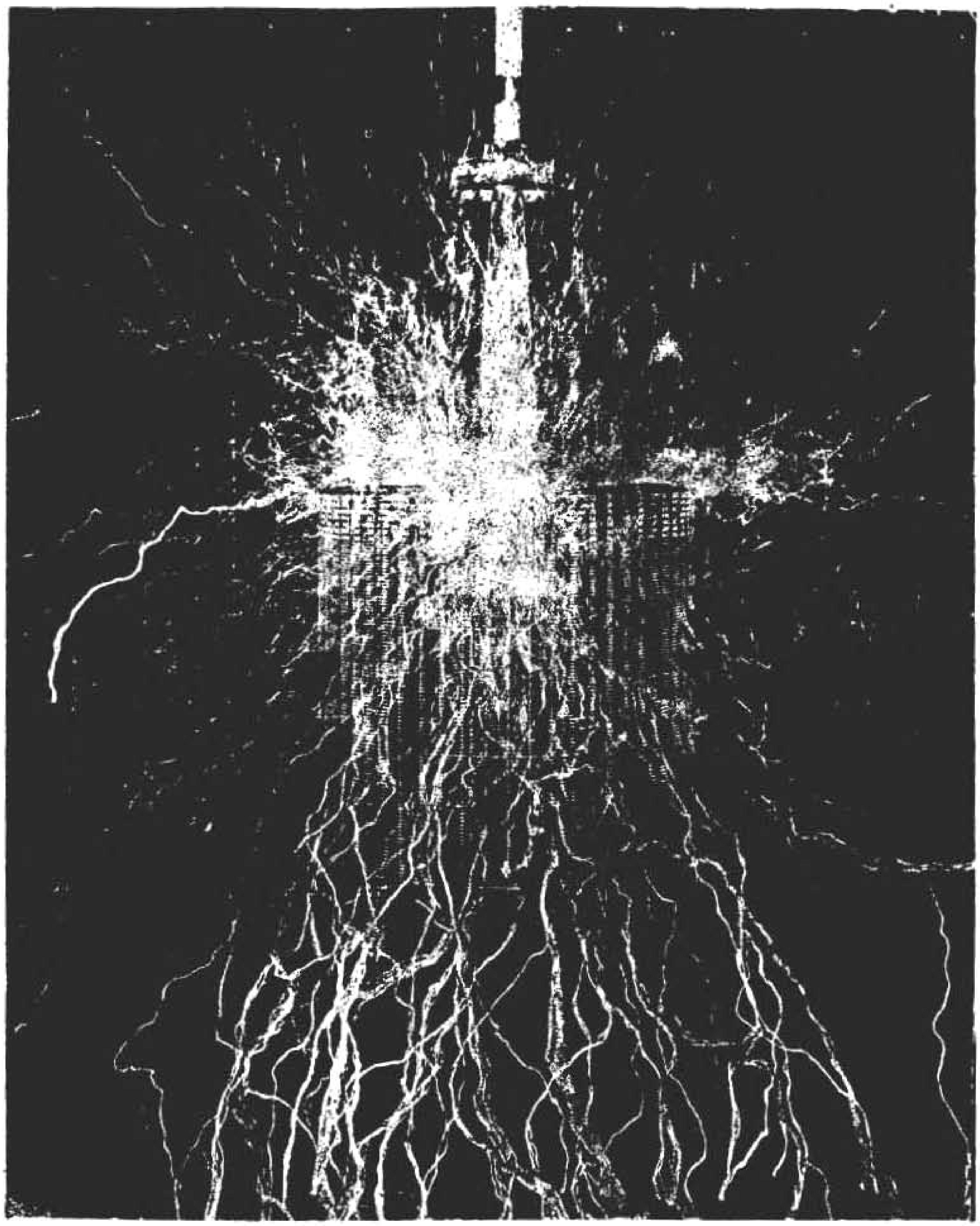
VII. View of "extra coil" in action. Wires slightly inclined to the ground, to prevent discharge from going to roof, were fastened at small distances to brass ring on top of coil. Thus a great amount of streamers was produced and they were necessarily weaker individually. The plate illustrates well this feature as is evident from the hairlike appearance of the streamers. Individual sparks passing to ground sometimes are strong. It is peculiar that discharge will break out more strongly on some wire and then keep on the same place until broken by draught created or otherwise. The path is, however, evidently accidental depending probably on the arrangement of particles floating in the air. This photograph is very beautiful and symmetrical. The length of the streamers is about the same as in preceding case. The vibration of "extra coil" system about normal only slightly modified by the wires attached to brass ring. Some streamers, curious to note when striking the ground and thus becoming *sparks* or spark discharges more brilliant in color, appeared thicker on bottom than on the point of origin. I believe I have recorded this phenomenon some time before. It may, on the plate, appear that the streamer or spark is thicker farther away from the origin without necessarily being so. This is simply caused by the end or lower part of the streamer being closer to the camera than the origin. But the eye is not deceived in this respect and the phenomenon may be frequently noted so that its existence is beyond doubt. This may be explained by assuming a volatilization of the material where the spark strikes, whereby a flame may be produced increasing the brightness of the part of the luminous path nearer to this point. In fact I observe that whenever a powerful spark strikes an object which is of a material easily disintegrated by the heat, such as wood, there is a momentary small flame produced on that point and often one may see the spark bound back as it were or splash over the object like a jet of molten metal. It will be noted on the negative that the points where the sparks hit the floor are always darker, this showing the increased development of light at these spots. The plate used is the same as before.

VIII. This shows a central view of "extra coil" normally excited with streamers issuing from a disk turned towards the camera. In this instance the streamers were longer than before as they were issuing from fewer points, chiefly from the rim of the disk which was a little more than 10" in diam. Some of the streamers darting towards the corners of the building were 30 feet in a straight line, but considering their curved path they were in all probability 50 feet long. Some of them show interesting bifurcations or splitting up in many branches while others, carried by the draught they create themselves, again show clearly the individual discharges. The brilliant sparks to the hood above the coil are also curious and interesting often passing far above the hood and then returning to the same in paths much longer than the straight route from the top of the coil to the hood which they should follow. Some of the streamers striking the floor show the increased brightness, before referred to, very clearly. It is noticeable that the streamers above the coil are of finer texture and split up, the draught being of course stronger near the opening of the roof. On some of the very long streamers one can see occasionally more brilliant points. The plate in this experiment was the same as before and the vibration of the "extra coil" system likewise normal or nearly so.

IX. This photograph illustrates again the extra coil with streamers and sparks from a pointed wire placed towards the camera. The wire or terminal was turned slightly downwards to cause the streamers or sparks to go more downward, as there was a considerable danger in this experiment of inflaming the roof of the building by the discharge taking an upward course. The streamers, when made to issue from a point as in this instance, are namely very long and in fact it was found impossible to work the apparatus to its full capacity in this account. The excitation of the "extra coil" system was pushed as far as could be done without great risk. The longest streamers reached the side of the building and even the corners sometimes. One of them reached the photographer Mr. Alley in the corner of the building, while another one struck me as I was operating the switch in another corner. They were so feeble at that distance, however, that they did not cause any injury or pain. Another one struck the camera but, as subsequently found, did not spoil the plate. These streamers were about the longest produceable in the present building, with the roof closed, measuring from 31—32 feet in a *straight line* from origin to end. Taking into account the curiously curved path the length was probably more than twice this, so that taking the discharge from tip to tip of these longest streamers, the *actual* path of the discharge through the air was from, say, 124—128 feet! If the building would permit I think that with the present apparatus, by putting about two to three times the copper in the oscillator a discharge extending through approximately twice this distance would be obtained, and by overcoming some defects of the present type of oscillator a further gain of about 50% could still be effected, so that I can certainly expect to reach, measured in this way, a length from 372 to 384 feet from end to end. In an industrial plant



Phot. VIII. Central view of "extra coil" normally excited with streamers issuing from a disk turned towards the camera.

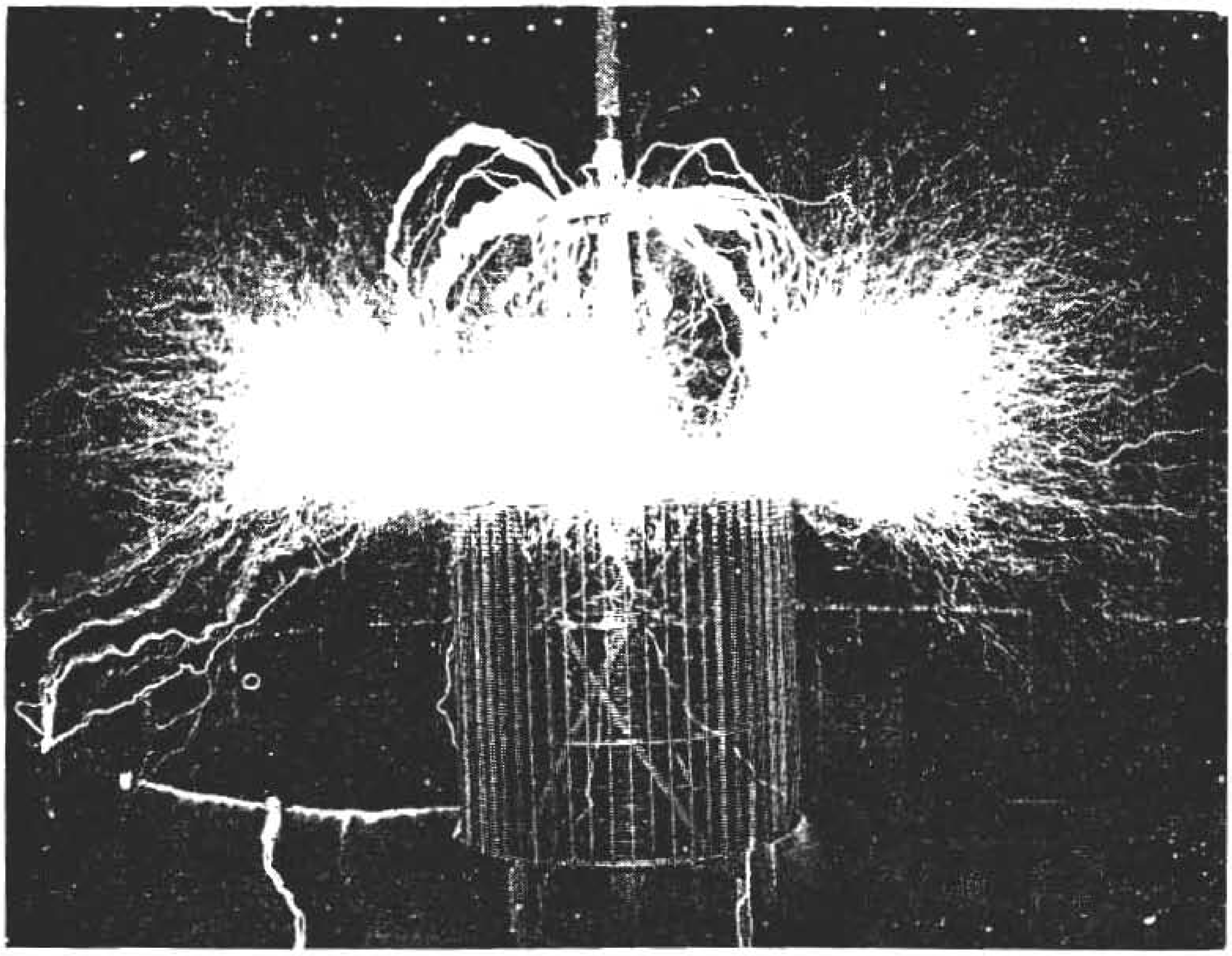


Phot. IX. "Extra coil" with streamers and sparks from a pointed wire placed towards the camera.

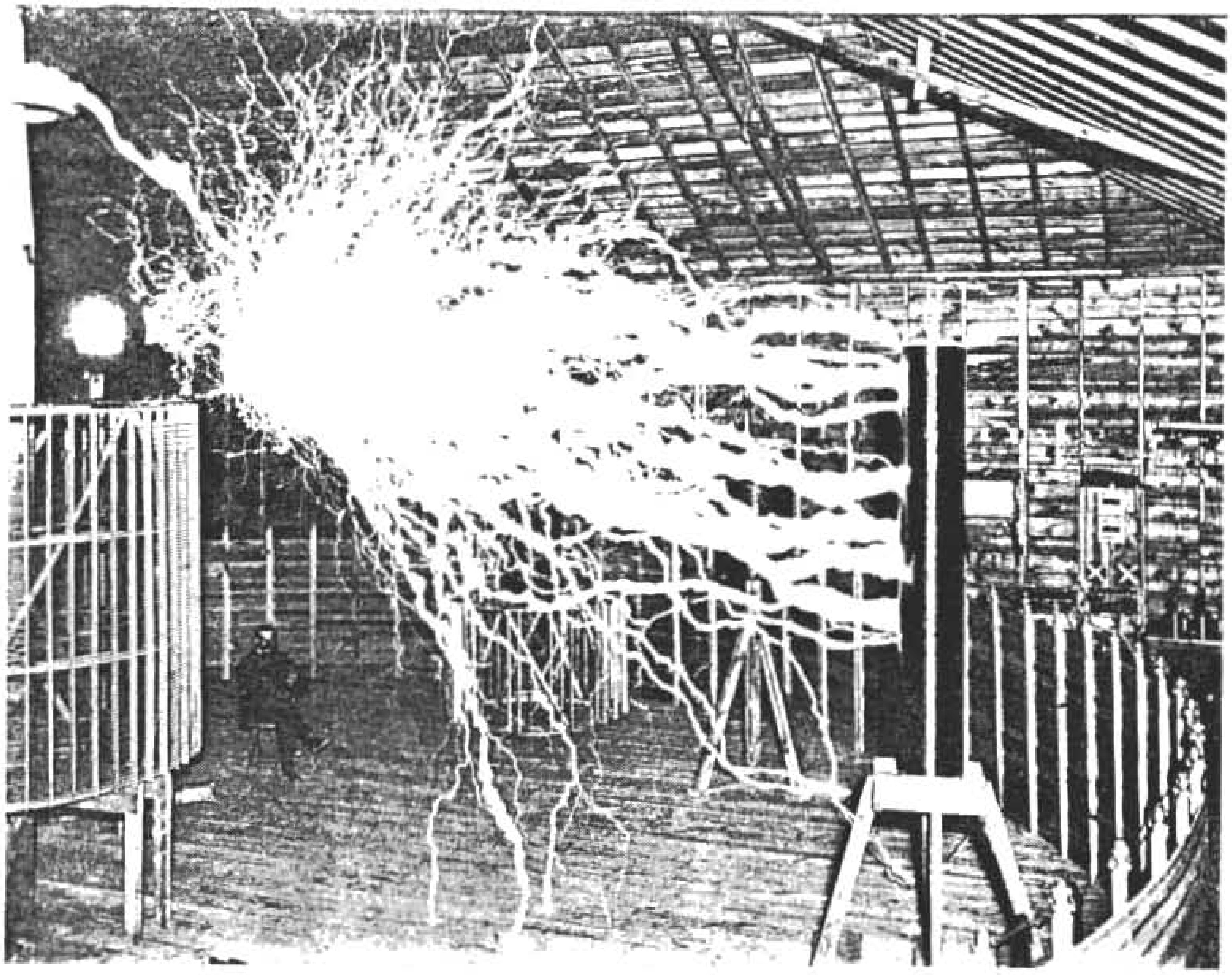
it seems to me advisable to push the pressure still further and the difficulties in this respect do not seem to me now to be very great. In the present photograph certain features before commented upon are even better shown than in the preceding plates. For instance, the high luminosity on the bottom where a spark strikes the floor, the "splashing" of the discharge, the branching out and the interruption of a streamer are all well shown. But the most curious feature is the appearance of "fire balls". As already noted in a previous instance a streamer even when not as strong as these here described, will show sometimes one or more points of greater luminosity than the rest. On a plate an effect of this kind may be produced by a streamer suddenly bending or turning, but the actual appearance of these luminous spots or points is unmistakable. In the instance here described the streamers were very powerful and the spots when they appeared were about an inch or possibly more in diameter, actual "fire balls" as they appeared to the eye. Now what is the cause of their formation? I attribute them to the presence of some material in the air at that particular spot which is of such a nature that when heated it increases the luminosity. It is possible that sodium is concerned in the production of the phenomenon. But the luminous "ball" must be extremely short lived as it does not impress itself upon the plate sufficiently despite its high luminosity. One can barely note a small luminous patch on the streamer, the impression of the central portion of the "ball". It is not improbable that the evolution of the "fire ball" may be connected with a process akin to explosion or sudden volatilization. Again, in this instance the same kind of plate was used and the vibration of the extra coil was but slightly quicker than normal.

X. This plate illustrates the discharge issuing from the top of the "extra coil", from the brass ring mentioned before, all over its surface. To produce a more beautiful effect in this instance the switch was thrown in 200 times, but the closure of the circuit was as short as was practicable, only a small fraction of a second, possibly 1/4 or 1/5 of a second. In plates VII, VIII and IX one hundred closures of the switch were made. This photograph is extremely beautiful although the streamers were not so large as in some previous instances. The sparks darting occasionally to the hood rather heighten the effect. The streamers are of fine texture but not quite so as in the plate described under VII. The reason is that the brass ring before mentioned, being of a large diameter, does not permit the streamers to issue from it as readily as the thin wires do and therefore the streamers partake more or less of the nature of sparks, being thicker and more brilliant and bluish white in color at the origin, while the streamers issuing from pointed terminals are of a reddish hue, sometimes quite purple and also less noisy and of feebler luminosity. Owing to their color and small luminosity they do not impress themselves upon the plate as powerfully as the streamers coming from surfaces of a relatively large radius of curvature, which are more or less of a disruptive character, ressembling sparks at the point of issue from the terminal. In this experiment again the vibration of the extra coil was nearly normal, the plate was of the same kind and the exposure to the arc light, as in the previous cases described, about 15 minutes, about half of the light cut off on lens.

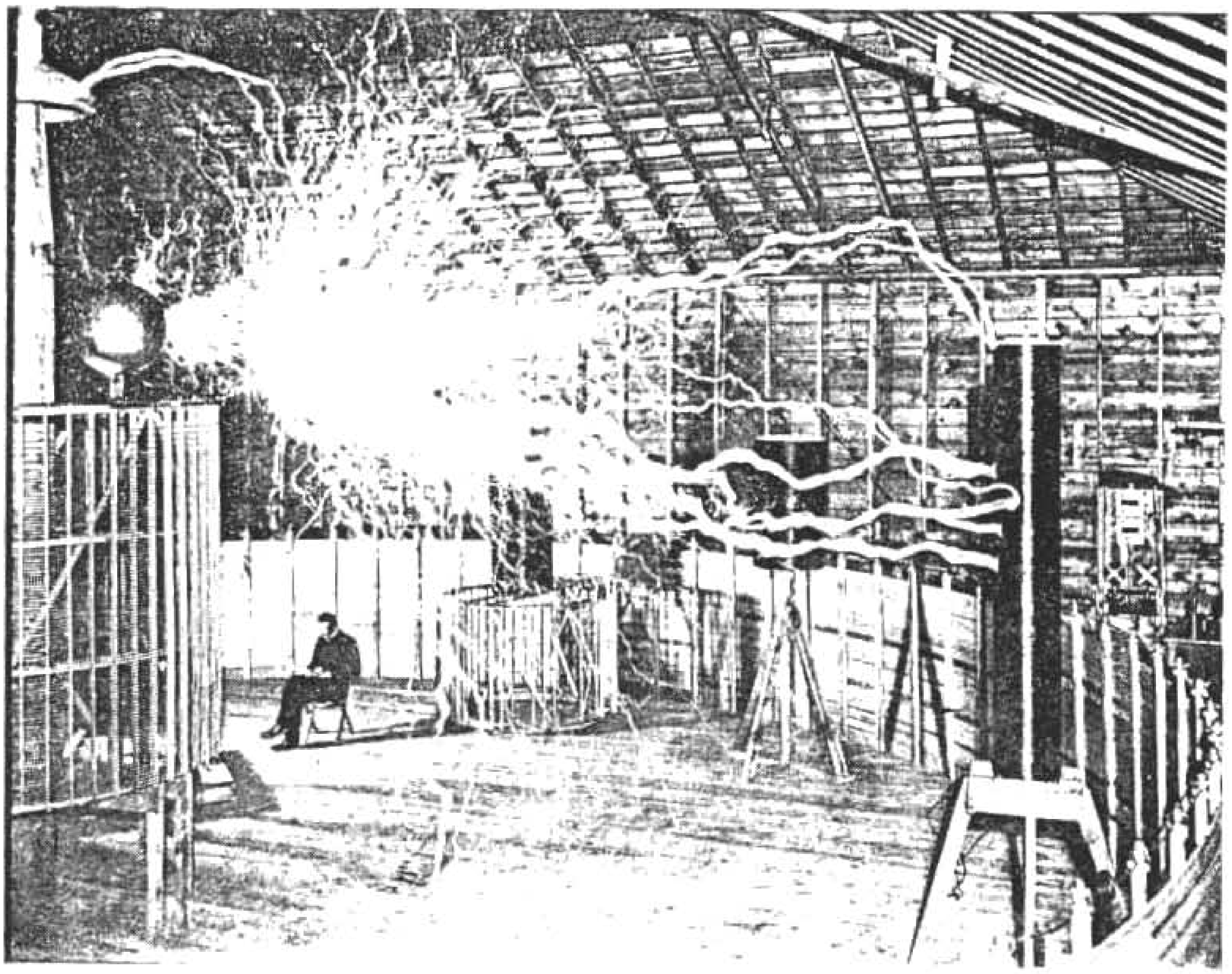
XI. Plate illustrates discharge passing laterally to the camera from the central coil across the shop to another coil on a vertical stand. The length of the sparks I estimate about 15 feet in this instance, possibly more. The sparks are very powerful and brilliant. The discharge was produced by 50 successive short closures of the switch, the experiment being, of course, performed in the dark. Then an exposure — with the arc lamp 10 min. lens almost open, with an experimenter (Mr. Alley) sitting in the chair — was made. The picture of a human figure was introduced to give an idea of the magnitude of the discharge.



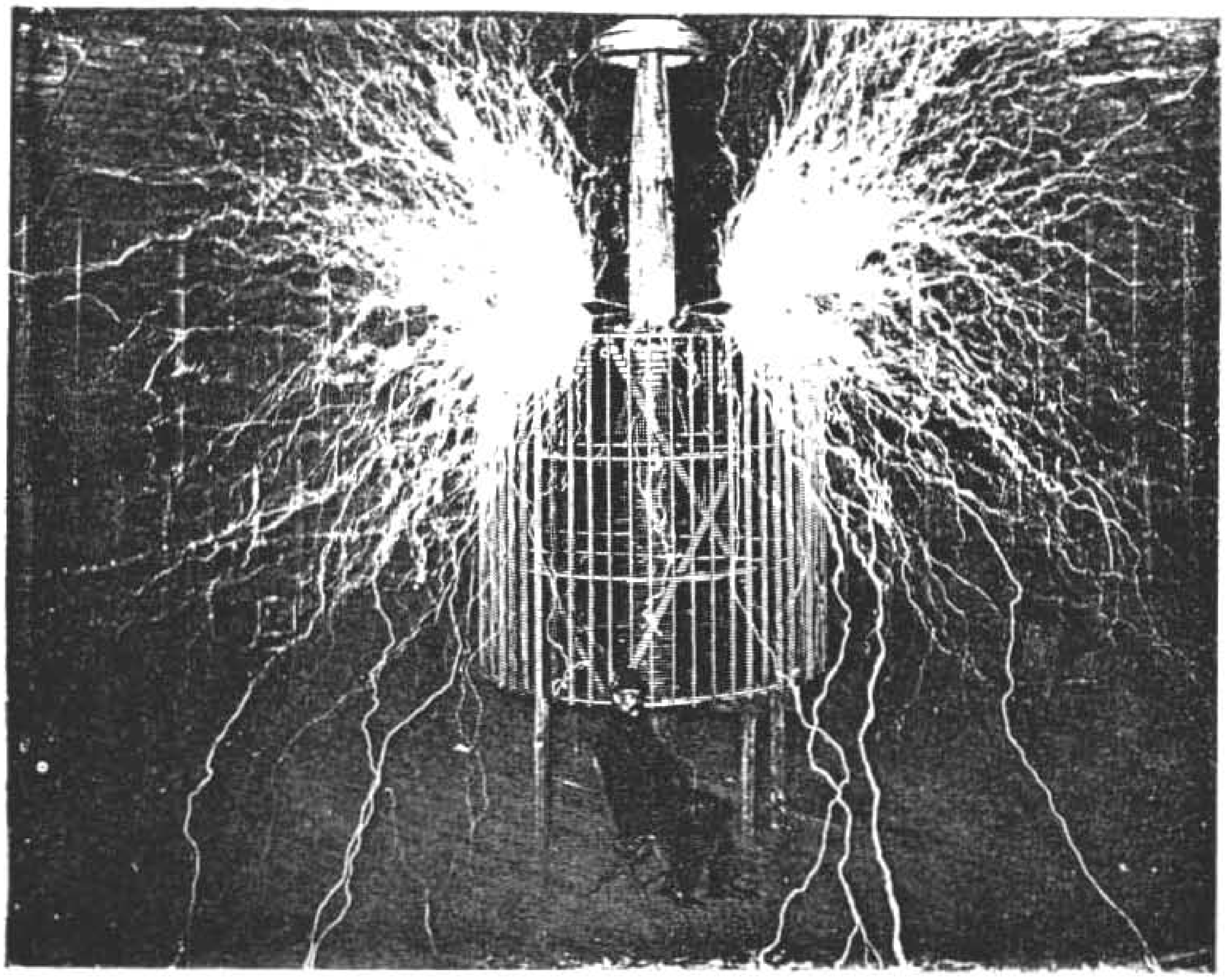
Phot. X. The discharge from the brass ring on the top of "extra coil".



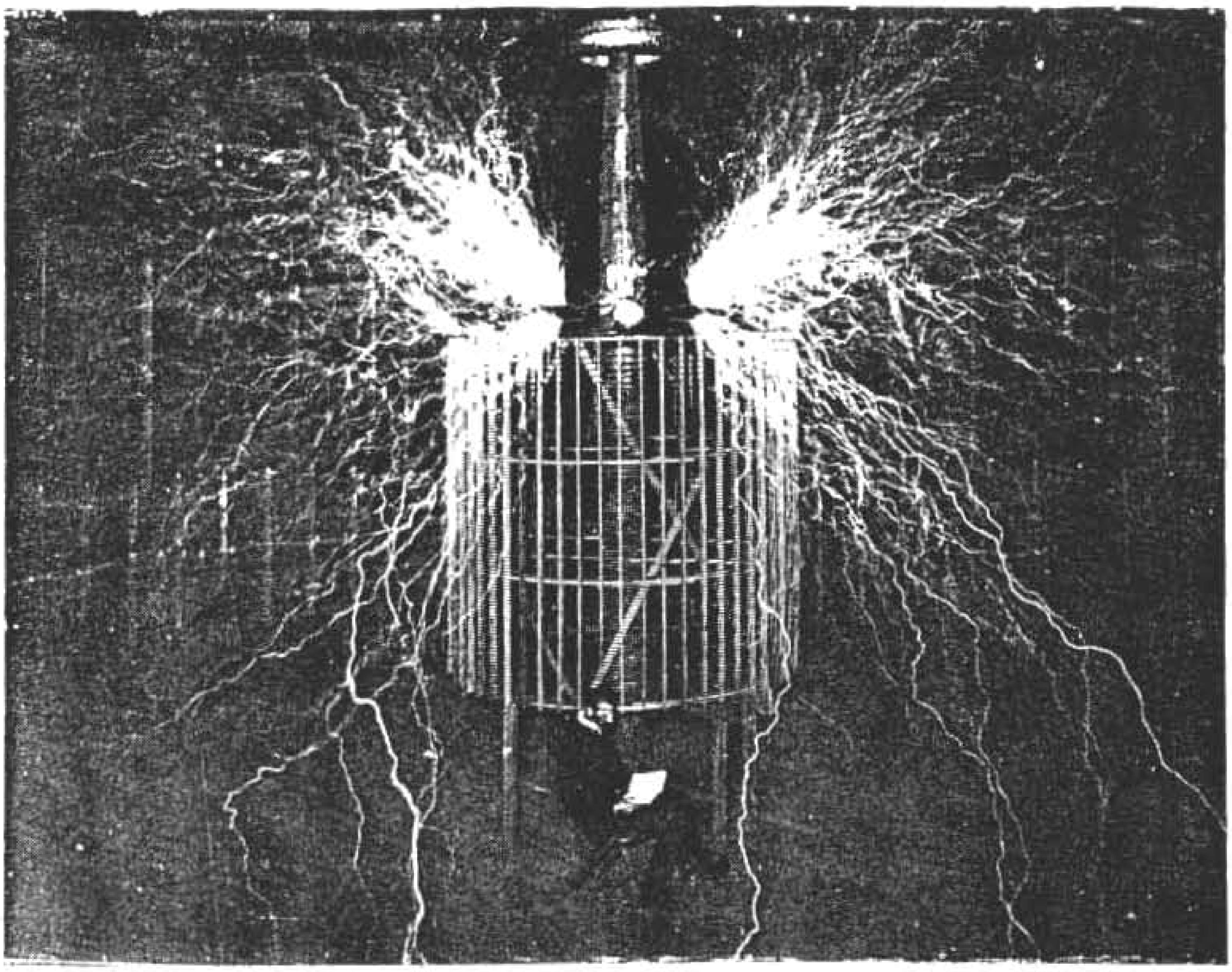
Phot. XI. Discharge passing laterally to the camera from the central coil to another coil on a stand. Mr. Alley is sitting in the chair.



Phot. XII. Repeated experiment shown in phot. XI, but with Tesla sitting in the chair.

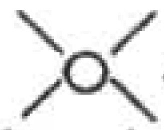


Phot. XIII. Streamers issuing symmetrically from ball with two wires on each side. Mr. Alley is sitting.



Phot. XIV. Repeated experiment shown in phot. XIII with Tesla sitting.

XII. The same experiment was repeated with the coil on stand being placed farther from the central coil. The sparks were about 20 feet long in a straight line. Fifty throws of the switch were used as before. The procedure was slightly modified by setting off about 1/3 of an Eastman flash powder to bring out my features.

XIII. }
XIV. } In these two plates the effect was improved by making the streamers issue symmetrically from ball 8″ diam. with two wires on each side: . Fifty throws of the switch were used and the procedure was as in XII. In all the later instances described the plates and other particulars were the same as before.

Note: *open lens, arc light 5 min.*

Note: to preceding description of photographs taken with Mr. Alley:

As before stated, in most cases when the "new extra coil" was shown in action, the vibration of the system including it was about the normal, only slightly modified by the attachment of terminals of comparatively very small capacity. The "extra coil" system was namely adjusted to the vibration of the primary system which took place with *one primary turn* (the two primary cables being in multiple) *with all the jars being connected in two sets in series* and with the *regulating coil all but* 1/2 *turn out*. Under these conditions the secondary was very strongly reacting upon the primary modifying the inductance of the latter so that the inductance of the primary turn instead of being as previously determined about 57,000 cm was diminished to 41,000 cm approx. Now the inductance of the connections to the condensers, and 1/2 of one turn of regulating coil, was as will be seen with reference to the table, often referred to — nearly 6000 cm. So that the total inductance of the primary circuit under these conditions, was owing to the resonating secondary, was only 41,0C0+ +6000=47,000 cm, or $\frac{47}{10^6}$ henry. Now the capacity in the primary was two sets of eight tanks in series or four tanks total, that is, $4\times 36=144$ bottles or $144\times 0.009=0.1296$ mfd, approx. Hence the period was

$$T_p=\frac{2\pi}{10^3}\sqrt{0.1296\times\frac{47}{10^6}}=\frac{2\pi}{10^6}\sqrt{6.0912}=\frac{2\pi}{10^6}\times 2.47=\frac{15.512}{10^6}$$

or n=**64,466** per sec. or nearly so. This is a considerably quicker vibration than when the secondary is not active. As the "extra coil" did not have sufficient inductance in itself, another coil was inserted in series with the same to insure the resonating condition with the above primary vibration. This latter coil was wound with wire No. 6 on an old drum 2 feet diam. and 6 feet long. Particulars about this coil will be recorded on another page.

Colorado Springs Aug. 14. 1899

In some experiments with coil having 1314 turns wound on drum 14" diam. & [illegible] feet long the coil was cut in the middle and the two parts 657 turns each connected in multiple. The selfinduction was then practically $\frac{1}{4}$ of the selfinduction which it had when ordinarily. Readings were taken to determine the inductance when the two parts were connected as stated.

These readings were:

$$E.m.f. \begin{Bmatrix} 214 \\ 212 \\ 210 \end{Bmatrix} \quad C \begin{Bmatrix} 10.7 \\ 10.6 \\ 10.5 \end{Bmatrix} \quad \omega = 880$$

Average values: E 212, C 10.6, ω 880

$R = 7.9$ ohm.

from this $\left(\frac{E}{C}\right) = 20$, $\left(\frac{E}{C}\right)^2 = 400$ $\quad R^2 = 62.41$

$$\left(\frac{E}{C}\right)^2 - R^2 = 337.59 \qquad \sqrt{\left(\frac{E}{C}\right)^2 - R^2} = 8.375$$

$$L = \frac{18.375 \times 10^9}{880} \text{ Cm.}$$

$= 20880682$ Cm. appr. $= 20,881,000$ Cm.

The inductance of the coil as ordinarily used would then be approx.

$= 83\,524,000$ C.m.

Colorado Springs Notes

Jan. 1—7, 1900

Colorado Springs July 11. 1899.

Now $A = \frac{\pi}{4} D^2$ $l_1 = N(T+d)$ hence the inductance will be $L = \frac{4\pi \cdot \frac{\pi}{4} D^2 N^2}{N(T+d)10^9} = \frac{\pi^2 D^2 N}{(T+d)10^9}$ henry. Taking these values for L and C we have with reference to above $\frac{1}{p^2} = \frac{\pi^2 D^2 N}{(T+d)\,10^9} \cdot \frac{l\,d\,D}{T \times 9 \times 10^{11}} K$ or $p^2 = \frac{(T+d)T \times 9 \times 10^{20}}{\pi^2 D^3 d\, l\, N K}$. Since in the preceding the diameter of the drum is assumed from practical considerations it will be convenient to find the number of turns N. The quantities D and T are of course interconnected, since by assuming D and deciding on the pressure to be obtained beforehand T is practically given. The diameter of the wire will in most cases also be selected beforehand so that then merely N is to be determined to satisfy the condition of resonance for any frequency specified. Now $l = \pi D N$. hence substituting this we have from above:

$p^2 = \frac{(T+d)T \times 9 \times 10^{20}}{\pi^2 D^3 d N\, \pi D N K}$ or $p^2 = \frac{(T+d)T \times 9 \times 10^{20}}{\pi^3 D^4 d N^2 K}$ and from this we get $N^2 = \frac{(T+d)T \times 9 \times 10^{20}}{\pi^3 D^4 d p^2 K}$ or $\underline{\underline{N = \frac{3 \times 10^{10} \sqrt{(T+d)T}}{D^2 p \sqrt{\pi^3 K} \cdot \sqrt{d}}}}$ .... This formula may serve to give an approximate idea how many turns are to be wound on in cases when the length of the wire, owing to the capacity in the excited circuit is smaller than $\frac{\lambda}{4}$, (or respectively smaller than $\frac{\lambda}{2}$, if the circuit is not one of the kind illustrated in diagrams above, that is one, in which the potential on one terminal is always higher than on the other, but an ordinary circuit, in which there is a symmetrical rise and fall of pressure at both the terminals), but the equation assumes that the dielectric constant is = 1 or nearly so.

Jan. 1, 1900

Photographs taken Dec. 22. and 23; with Mr. Alley from Dec. 17 to Dec. 31, 1899 and *particulars* about the same:

XV. Shows an incandescent lamp 16 c.p., 100 V placed out on the field with two wires leading to it. Snow on the ground. The lamp is lighted.

XVI. Illustrates the same with three lamps 16 c.p., 100 V placed on the snow and lighted. The lamps are connected in multiple arc.

XVII. Photograph showing once more the same with three lamps as before, the lamps being placed on black cloth to improve effect. These photographs were taken under the following conditions:

A cord of section equal to that of wire No. 10 was laid on the field in the form of a square of 62′ 5″=749″=*1902.5 cm* side, the center of the square being from the center of the primary loop of the oscillator in the laboratory a little over 60 feet=720″=*1830 cm.* The ends of the square were connected to two small condensers joined in multiple and each having a little less than 1/20 mfd. Neglecting capacity of the cord against that of the condensers the total effective capacity of this system was, with fair approximation 1/10 mfd, or *90,000 cm.* The inductance of the square, taking it as consisting of two pairs of parallel wires, was

$$L_s=2\times 2\,l\left(\log_e \frac{d^2}{r\,r'}+1/2\right).$$

In the present instance

$$l=1902.5 \text{ cm},\qquad d=1902.5 \text{ cm},\qquad r=r'=0.254 \text{ cm}.$$

$$\frac{d^2}{rr'}=\frac{d^2}{r^2}=\left(\frac{d}{r}\right)^2=\left(\frac{1902.5}{0.254}\right)^2=(7500)^2 \text{ and } L_s=4\times 1902.5\times$$

$$\times(\log_e 7500^2+1/2)=7610\times(17.825+0.5)=7610\times 18.325=761\times 183.25$$

log 7500=3.875061 $\qquad L_s=139{,}450$ cm, or $\dfrac{13{,}945}{10^8}$ henry

2 log 7500=7.750122

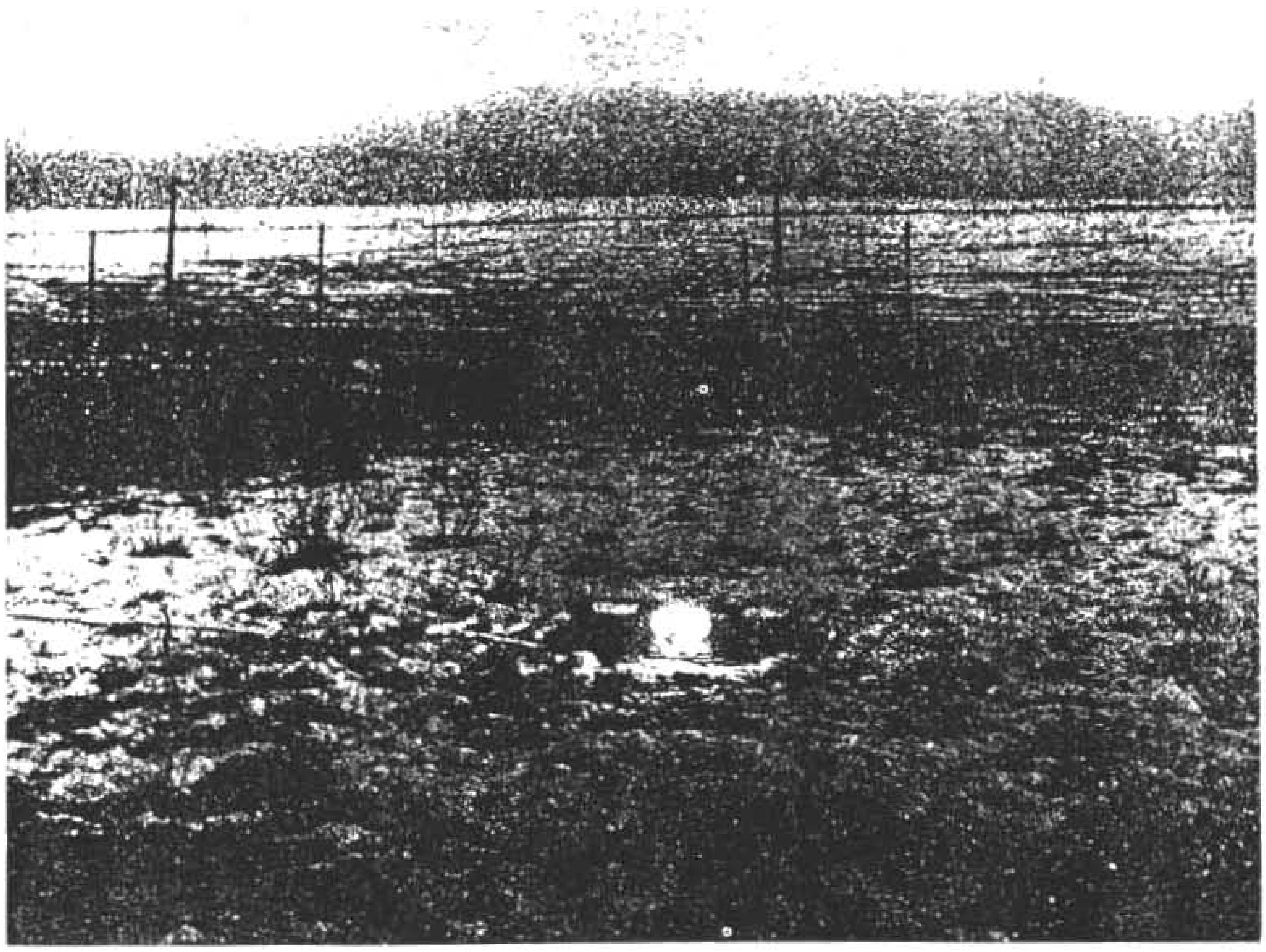
2 $\log_e$ 7500=7.75×2.3=17.825 approx.

From the foregoing we have for the period of the secondary system:

$$T_s=\frac{2\pi}{10^3}\sqrt{0.1\times\frac{13{,}945}{10^8}}=\frac{2\pi}{10^7}\sqrt{1394.5}=\frac{2\pi\times 37.34}{10^7}=\frac{234.5}{10^7}$$

and this would give $n=42{,}640$ approx. per second.

Now resonance in this circuit was obtained with all jars being connected as usual and two primary turns in multiple, there being besides in the primary circuit 18 1/2 turns of the regulating coil. This gives approximately the capacity of primary or exciting circuit $\frac{8\times 36}{2}$ jars=144 jars or bottles=0.0009×144=0.1296 mfd. Neglecting for the moment



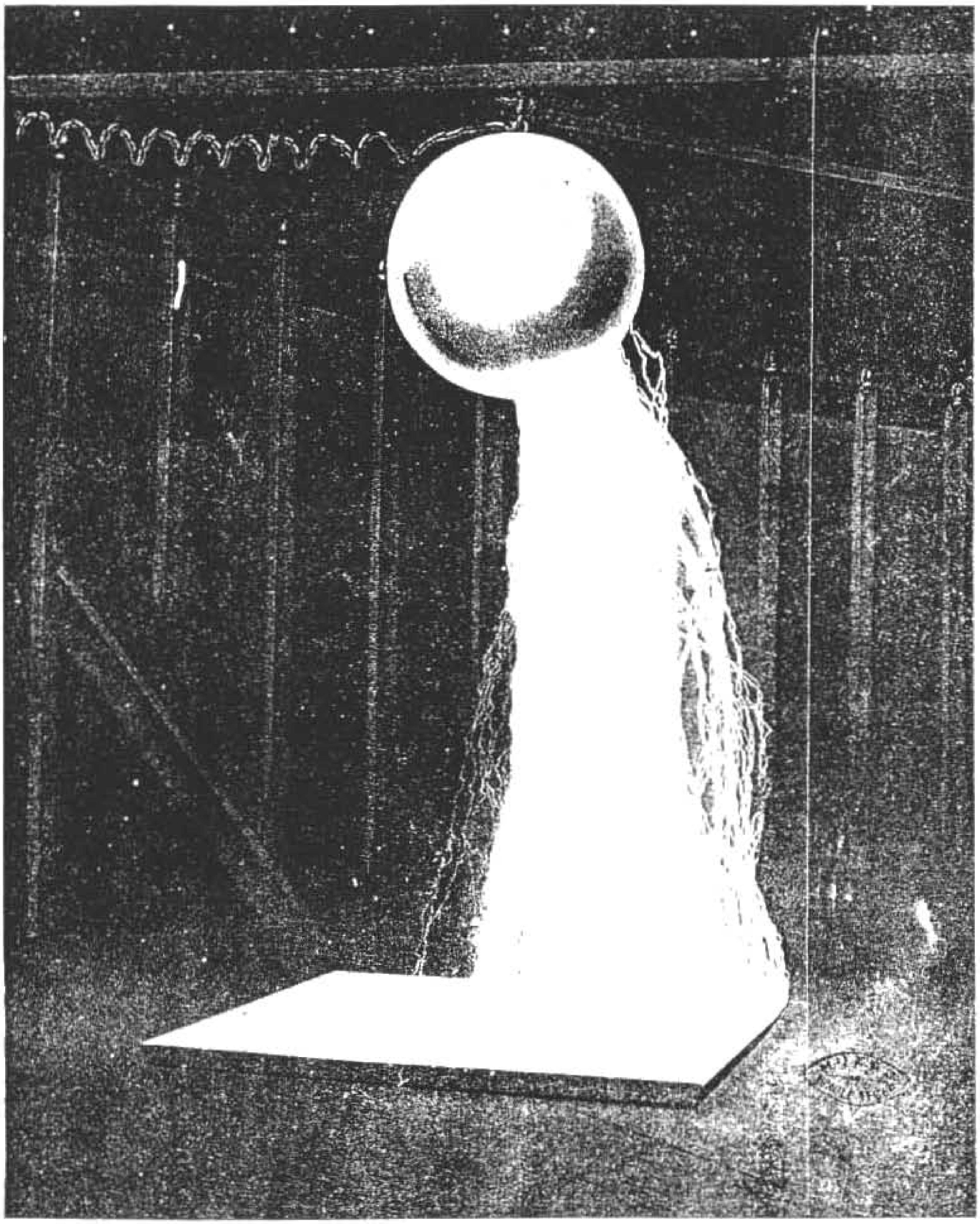
Phot. XVII (?) Experiment to illustrate an inductive effect of an electrical oscillator of great power. The photograph shown is reproduced from Tesla's article[41] in which somewhat different circuit dimensions and position are quoted.

the secondary reaction (that is the action of the secondary of the oscillator upon the primary, the former being thrown out of step by connecting some inductance in series with it), the inductance of the primary circuit with reference to previous data for the primary turns and regulating coil was 122,000 cm. But the inductance calculated from equation

$$\frac{2\pi}{10^3}\sqrt{0.1296 \times L_p} = \frac{2\pi}{10^3}\sqrt{0.1 \times \frac{13,945}{10^8}} = \frac{234.5}{10^7}$$

is smaller, being in fact only about *108,000 cm*. The smaller value is evidently the correct one, being the actual value of the inductance of the primary circuit, as modified by the secondary of the oscillator and the secondary circuit lighting the lamps. A small streamer was seen to issue from the free terminal of the secondary, hence it certainly affected the primary, reducing the inductance. The reaction of the secondary circuit lighting the lamps was comparatively small. In order not to burst the lamps the current of the supply transformers was very much cut down. I think about 30 lamps could have been lighted in this manner by pushing to the normal limit the excitation of the primary loop.

Four photographs were made of the discharge of the secondary of latest type, 20 turns of two wires No. 10. The primary consisted of one turn, the two primary cables being connected in multiple arc. The ratio of conversion being thus 1 : 20, the e.m.f. at the terminals of secondary, with the primary excited to full power, was about 400,000 volts. Owing to the low resistance of the secondary — extremely low when considering the high e.m.f. — the discharge was very powerful, of a dazzling brilliancy, literally blinding, and caused a deafening noise. The candle power of the arc is equivalent to that of five or six arc lights of normal strength. At least I conclude so from comparative tests. Photographs were made by exposing the objects to the light of the secondary discharge and it took only a small fraction of the time needed for an arc lamp to impress the plate. The secondary discharge of this apparatus is so powerful that it was always more or less dangerous for the safety of the laboratory and machinery in the same, and elsewhere, to let it play. A number of times the shop caught fire by sparks passing from some nail, wire or any kind of conductor. When the discharge was playing sparks were seen to fly almost everywhere through the laboratory, from one to another object and it was evident that it was more or less risky to let the sparks from the free terminal pass to the ground, because short waves were produced in the conductors and these were only too apt to rupture the insulation of any apparatus in the circuit or circuits connected with the oscillator or in the neighbourhood of the same. The danger resides chiefly in the *short* waves and the risk was considerably diminished when the secondary, instead of discharging directly into the short ground connection, was made to discharge through a coil or inductance, slowing down the vibration and preventing the formation of *very* high harmonics. When the discharge was effected as in the experiments photographed, a continuous and brilliant arcing took place over the lightning arresters and the dynamo at the supply station was short-circuited in rapid succession. When considering that the arc on the arresters is almost continuous one must admit that these arresters work extremely well. The discharge, owing to the terrible noise it creates is highly irritating and I think also dangerous to the timpanum of the ear. Often pain is experienced in the ears afterward and the buzzing in the ears continues for hours. If signalling with *very short* waves were desirable, nothing better could be used than such a secondary discharge. Although I have not tested its effects at extremely great distances, I conclude, from comparison with other induction apparatus experimented with, that it would affect a sensitive device certainly at one thousand miles



Phot. XIX. Discharge between a ball of 30" diam. and the ground plate.

and very likely at a greater distance, even on land. The great brilliancy of the discharge is in part due to the comparatively large capacity of the secondary which, as before shown, is without further provision inseparable from such a coil of very large diameter. When looking at the arc for a moment one can clearly perceive the arc proper forming the central and comparatively narrow part of the luminous path, around which there is on each side a brilliant band of 1/2" to 1" width apparently. When the discharge is playing, generally sparks pass on some places between the secondary top turns, this showing that they are by no means too far apart.

Of the four plates: XVIII., shows the secondary discharging from the free end or terminal formed by a wire to the ground plate visible on the bottom.

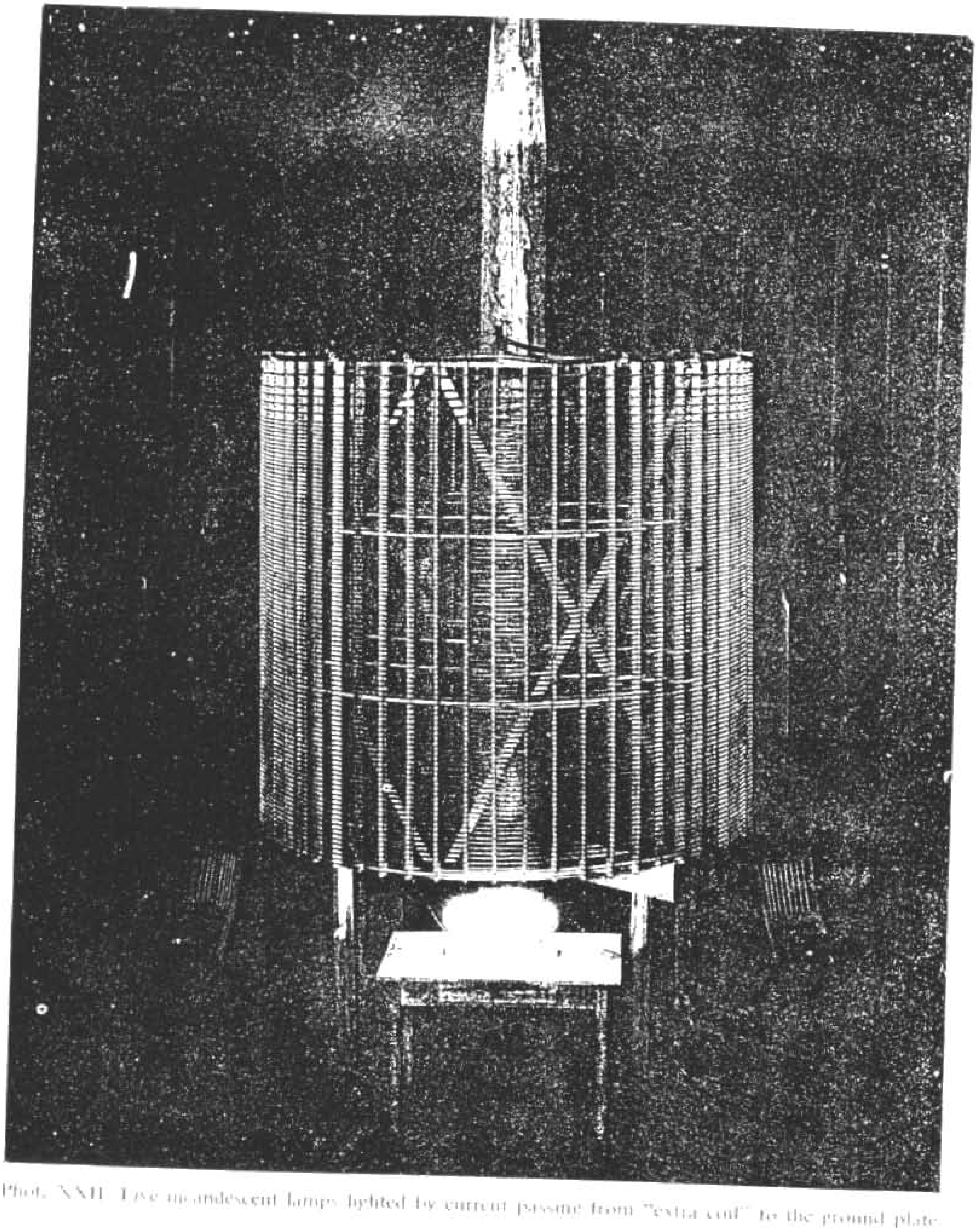
Plate XIX. illustrates the discharge taking place between a ball 30" diam. and the ground plate. In the former case the discharge is about 3 1/2 feet, in the latter about 3 feet long. These photographs were taken through about half of the full lense opening, nevertheless the discharge is not sharp for although the focusing was carefully effected the wide luminous band on each side of the arc proper, which was referred to, blurs the image. To improve the photographs two more plates were exposed, one the same as plate XVIII., marked XX., showing discharge between a wire and ground plate, and the other, marked XXI., illustrating discharge playing between a ball 18" diam. and the ground plate. In these instances a small opening was used and the images are sharper. To be quite sharp a pin-hole diaphragm should be used. The vibration in these four instances was the normal as before determined, all jars and one turn in primary, 25 throws of switch, very short, flash afterwards.

Colorado Springs

Jan. 2, 1900

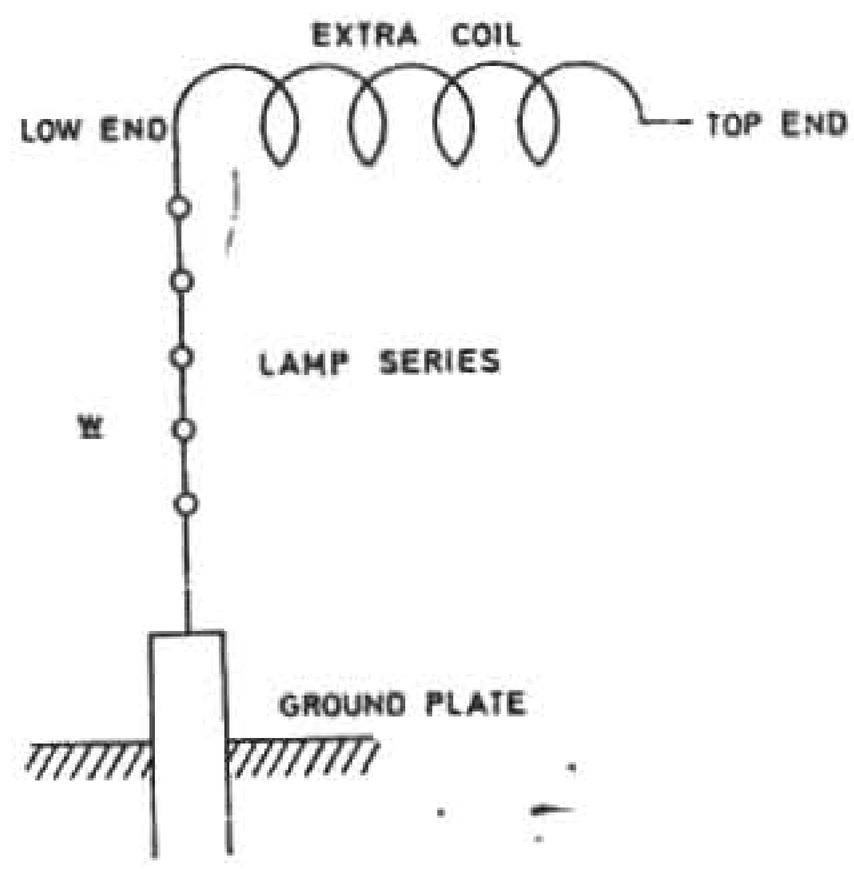
Photographs taken with Mr. Alley from Dec. 17 to Dec. 31, 1899 and *particulars* about the same.

XXII. This photograph shows the "new extra coil" as last modified, having 98 turns wire No. 6 and on top two turns or nearly so of wire No. 10 covered with a thickness of 3/8" rubber. This wire was repeatedly referred to in previous notes. It was necessary to use it in many of the experiments recorded for the purpose of preventing or at least reducing leaks. In many cases despite the excellency and great thickness of the insulation the latter was found inadequate to withstand the strain, as is evident from a number of photographs showing the coil in action energized to full power. The picture illustrates five incandescent lamps lighted — and to much more than normal candle power — on a table in front of the coil. The lamps are in series, one end of the series being connected to the ground by a wire seen on the bottom while the other end of the lamp series is joined to the lower end of the coil, the upper end being entirely insulated and remote from objects which might act upon it inductively. The connection will be best understood from the diagram below. In the experiment illustrated there is no appreciable induction exerted



Phot. XXII. Five incandescent lamps lighted by current passing from "extra coil" to the ground plate.

upon the extra coil as the wires of the oscillator proper, wound on the wooden structure seen in the back behind the coil, are *short-circuited.* One of the terminals of the condensers is grounded so that when they are discharging through the circuit, chiefly composed of a number of turns of the regulating coil, there is a strong vibration propagated through the ground which through the ground wire w reaches the "extra coil". Now, generally, the energy which can thus be transmitted to the coil would be minute, but when the oscillations passing through the ground are exactly of the frequency of the "extra coil" system itself, a considerable current passes into the coil which then acts just as a hole would in a pipe through which a fluid is pumped by means of a pulsating piston. As the magnifying factor of the coil is very large the feeble impulses reaching the ground wire and lamps magnify the impressed e.m.f. and create considerable movement of electricity through the lamps which are thus brilliantly lighted, as shown in the photograph. In the experiment the capacity in the exciting oscillating circuit, impressing the vibrations upon the ground and wire w, was 3 tanks on each side or 1 1/2 tanks total, that is 54 bottles or $0.0009 \times 54 = 0.0486$ mfd, approx. The total inductance was 41,000 cm+ind. of 6 1/4 turns of regulating coil$=41{,}000+19{,}368=60{,}000$ cm, approx. or 0.00006 henry. From this the approximate period of the vibration impressed upon the ground would be



$$T_p = \frac{2\pi}{10^3}\sqrt{0.0486 \times \frac{6}{10^5}} = \frac{2\pi}{10^5}\sqrt{0.02916} = \frac{2\pi}{10^5} \times 0.1708 = \frac{1.074}{10^5}$$

approx. and $n=93{,}110$ and $p=585{,}000$ approx. λ would be very nearly 2 miles and $\frac{\lambda}{4}=1/2$ mile or about 2640 feet. In reality the length of the wire in the excited system — that is extra coil and ground wire, was found by measurement to be *2660 feet* (98 turns, wire No. 6, 25′ 11″ each turn$=2540'+3/4$ turn of cable inside of secondary frame$=$ $=112'+$continuation of ground cable outside of circle to ground plate$=28'+$wire $w=$ $=20'+$rubber covered wire on top of coil$=50'$ that is, total $2450'+112'+28'+20'+50'=$ $=$*2660* feet. From above data and taking resistance of extra coil at *1 ohm* (in reality a little less) we get magnifying factor for coil alone $\frac{pL}{R}=\frac{585{,}000 \times 0.018}{1}=$ *10,530.*

Taking, however, into consideration that the resistance of the lamps was about 1000 ohms roughly, when including the latter in the system the factor would be only about $\frac{1}{1000}$ of this, or approximately only *10.5*. But I believe that the resistance of the lamps when operated by currents of such extreme frequencies is much smaller than the measured resistance according to the usual methods. The currents, namely, when produced in such ways as these here employed, have very high maximum values and the carbon is brought periodically to a much higher temperature than when operated with steady currents or currents of ordinary frequencies. I have observed this repeatedly. Furthermore when such currents as these here are used some part of the discharge also passes through the rarefied gas in the bulb and there is a corresponding diminution of the effective resistance of the lamp on this account. In fact, I think that it is chiefly owing to this that the resistance becomes very small, it being a fact that such currents pass with the greatest freedom through the rarefied gas particularly when it is maintained at a high temperature, as in the case here considered. The heating of the gas has the effect of increasing the incandescence of the carbon and it is well demonstrated that an incandescent lamp takes, for a given luminosity, less energy when operated with currents of such extreme frequencies. Owing to these reasons the magnifying factor of the excited system even with the lamps included must have been very much larger than the figure last mentioned. It was astonishing to note, in the experiment recorded on the plate, how much energy can be in this manner conveyed to such a carefully synchronized coil through the ground. The supply transformers were cut down by a regulating coil in the primary to less than one half, in fact to about 1/3 of full capacity and inasmuch as only 3 tanks on each side in the primary or exciting circuit were used while 8 tanks were available, it is evident that, if the excited system would have been designed to work with *full output* of the exciting apparatus it would have been quite practicable to light, say $3 \times 8/3 = 8$ times as many lamps, or about 40 lamps. However, inasmuch as the five lamps were far above candle power it would have been, in all probability, possible to light 60 lamps or so to normal candle power by a specially designed coil, with a liberal allowance of copper, vibrating in unison with the system exciting the portion of the ground containing the ground plate. Nothing could convey a better idea of the tremendous activity of this apparatus and a simple comparison with well ascertained data, obtained with other induction apparatus, shows that one of the problems followed up here, that is the establishment of communication with any point of the globe irrespective of distance, is very near its practical solution. The existance of stationary waves proves the feasibility of the project almost beyond any doubt. The great amount of energy which can be conveyed to such a synchronized circuit, by conduction through the ground, makes it appear possible, that the necessity of elevating terminals in my system of energy transmission to a distance may be dispensed with in many instances and that, with a very moderate elevation of, say, a few hundred feet enough energy may be conveyed to a circuit to serve for one or another useful purpose beyond mere signalling, or such uses of the system in which a minute amount of energy is required. Certainly, the amount of energy conveyed in this manner was, in some experiments with this apparatus, surprising at first. An interesting consideration in this connection may be the following: As before stated the period of the exciting or primary circuit, when resonance with the extra coil was attained, was $T_p = \frac{2\pi}{10^3}\sqrt{0.0486 \times \frac{6}{10^5}}$. Now the period of the excited system was $T_s = \frac{2\pi}{10^3}\sqrt{0.018 \times C_s}$, in which C_s is the "ideal" capacity as designated in previous instances, that is the capacity which would have to be joined to the free end of the "extra coil" of inductance of 0.018 henry but devoid of all distributed capacity. Since $T_p = T_s$ we find $C_s = \dfrac{0.0486 \times \frac{6}{10^5}}{0.018}$ mfd, or

$$C_s = \frac{9 \times 10^5 \times 0.0486 \times \frac{6}{10^5}}{0.018} = \frac{54 \times 0.0486}{0.018} = \frac{54 \times 486}{180} = \frac{3 \times 486}{10} = \mathbf{145.8\ cm.}$$

Suppose an ideal system of this kind excited in the manner described, so that capacity on the free end is charged each time as the current alternates to a potential P. Then, since as before stated, the system in experiment illustrated was vibrating about 93,000 times per second, the total energy set in movement in the system would be

$$2 \times 93{,}000 \times \frac{P^2 \times 145.8}{2 \times 9 \times 10^{11}} \text{ watts.}$$

Let it be further assumed that 1% of the total energy set in movement is frittered down in the lamps and that the number of these were *60*, as might have been the case in the presently described experiment. Suppose each lamp to take 50 watts, the total energy consumed in the lamps would be 3000 watts hence, under the above assumptions, the total energy set in movement in the excited system would have to be 100 times this amount or 300,000 watts. To satisfy this condition we would have

$$2 \times 93{,}000 \times \frac{P^2 \times 145.8}{2 \times 9 \times 10^{11}} = 300{,}000$$

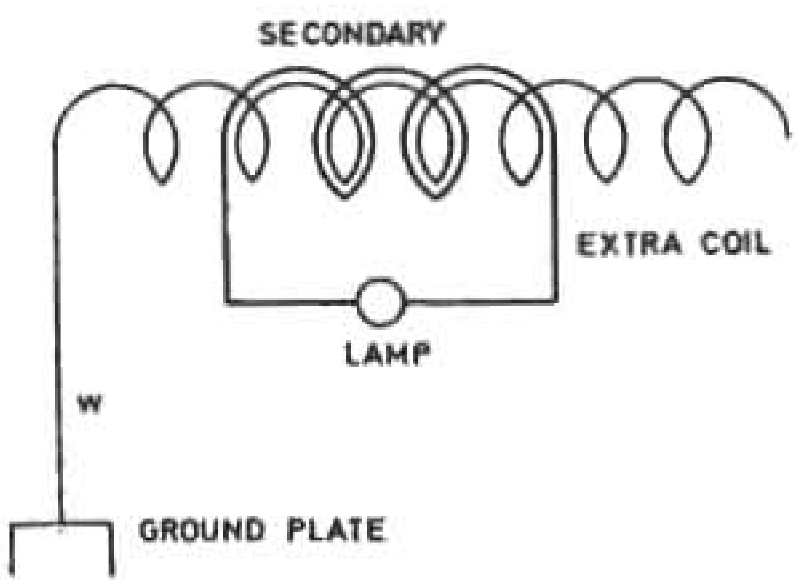
and

$$P^2 = \frac{54 \times 10^{13}}{186 \times 145.8} = 10^{12} \times \frac{540}{186 \times 145.8} \text{ or } P = 10^6 \sqrt{\frac{540}{186 \times 145.8}} \doteq$$

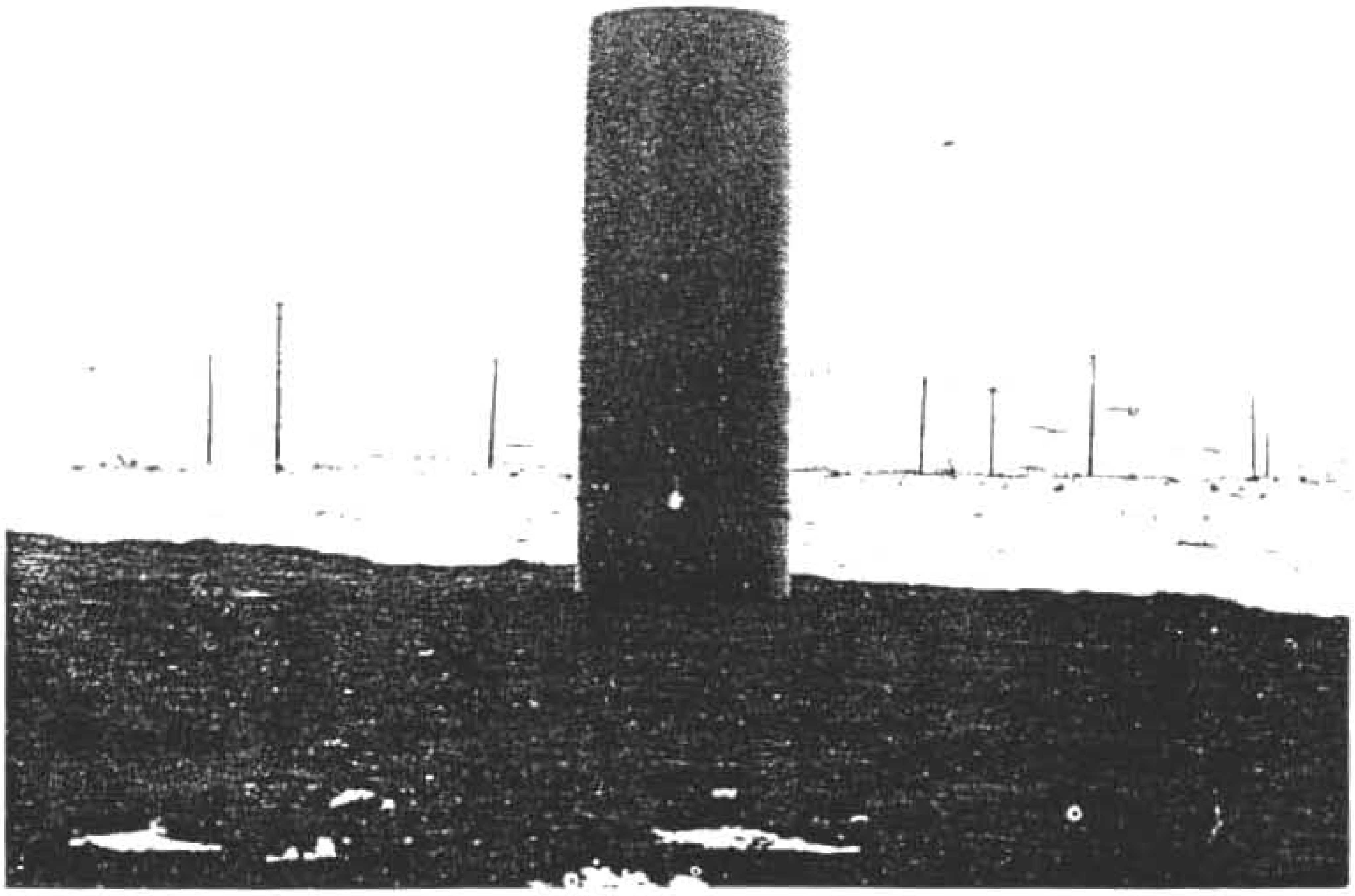
$$= 10^6 \sqrt{\frac{540}{27{,}118.8}} = 10^6 \sqrt{0.02} \text{ approx. or } = 10^6 \sqrt{\frac{2}{100}} = 10^5 \sqrt{2} =$$

$$= 10^5 \times 1.414 \text{ or } \boldsymbol{P = 141{,}400} \text{ volts.}$$

Not very much, as will be seen, for such a pressure is extremely small with apparatus of the kind used here. Taking P roughly as 140,000 volts and assuming that the ground plate be at such a distance that only 1000 volts are impressed upon the same then the magnifying factor would have to be only 140. Of course, this is merely an example to support the above statement that considerable energy may in this way, and by such apparatus, be conveyed to a distant circuit which is connected to the ground at only one point directly or, if desired, through a condenser.



In another photograph, marked Plate XXIII., taken with same apparatus a similar experiment is illustrated. Here the extra coil as indicated in the diagram above is connected directly through the wire w to the ground plate and another coil designated in the diagram as "secondary" is placed in inductive relation to the extra coil excited in the same manner as in experiment before described, and a lamp is lighted by the currents generated in this "secondary". Only one lamp was used as it was the object of the photograph merely to illustrate a novel experiment, but with reference to the above it will be understood that as many as *60* lamps, or nearly so, might have been lighted with the apparatus used in this manner. All the particulars were practically the same as before. The "secondary" had four turns, the excitation of the extra coil being reduced so that the lamp was somewhat above normal candle power. In this, as well as in the preceding experiment, the switch on the Westinghouse high tension transformer was thrown in and out



Phot. XXV. A coil outside laboratory with the lower end connected to the ground and the upper end free. The lamps is lighted by the current induced in the three turns of wire wound around the lower end of the coil.

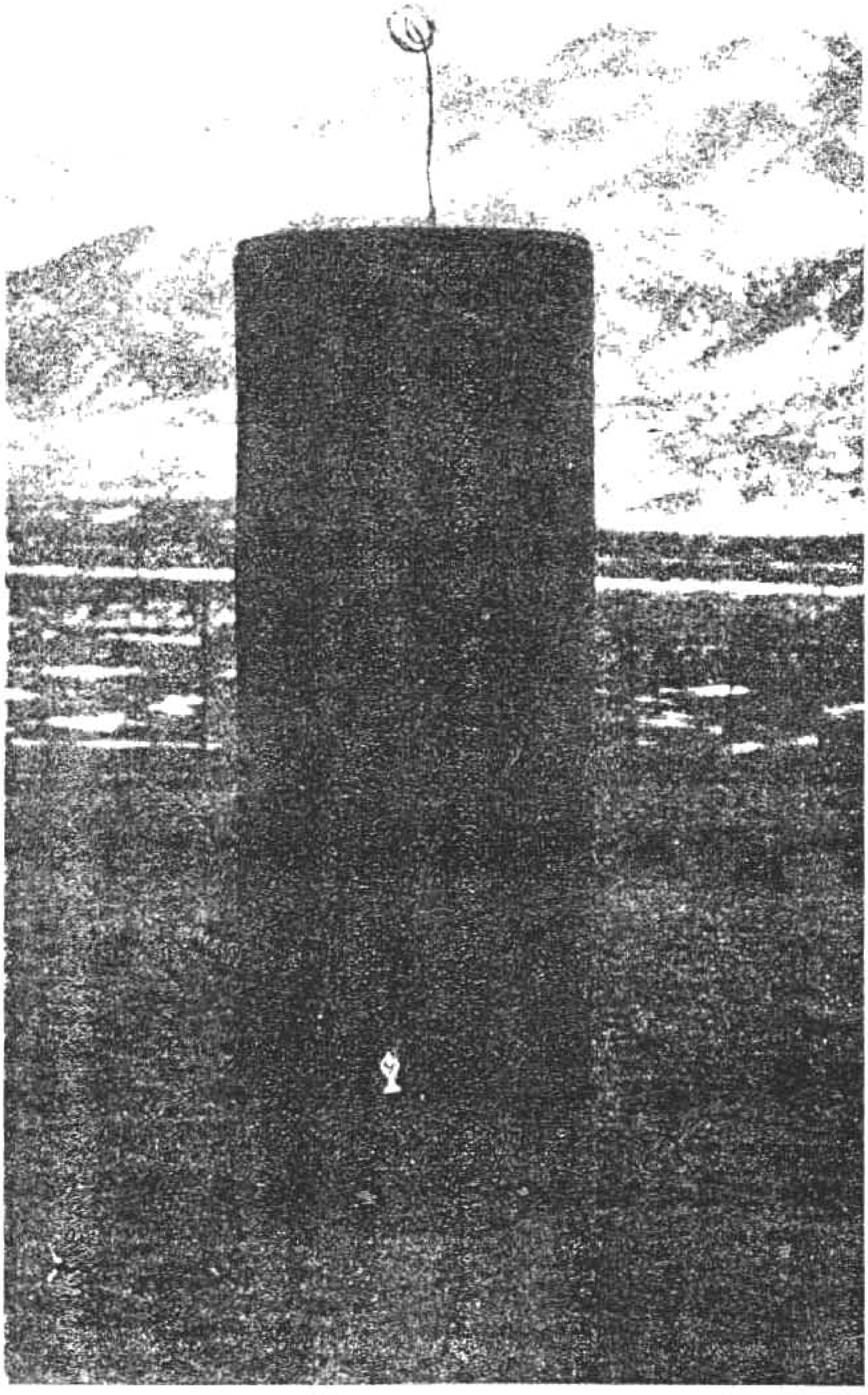
about 50 times and after this, as usual, an exposure to arc light for the detail of the apparatus was made, the time being 10 minutes with a small opening.

In order to make these two experiments still more interesting they were performed outside with a smaller receiving coil and photographs were taken, which are numbered and of which Plate XXIV. shows a coil standing outside on a table to which a groundwire leads, which is connected to one of the terminals of a small lamp, while the other terminal of the same is joined to the lower end of the coil. The upper end of the coil is free, a metal tube being connected to the same, as shown clearly in the picture. This tube is placed axially and serves to increase slightly the capacity of the excited system.

In another experiment, with the same coil illustrated in Plate XXV., the coil is placed on the ground away from the laboratory and the lower end is connected to the nearest ground, while the upper end or terminal is free. Three turns of wire are wound around the lower end of the coil and the ends of this wire are connected to a lamp socket with its lamp which is, as shown, lighted by the currents induced in the three turns of wire through the oscillations transmitted through the ground to the coil.

One more experiment of this kind was photographed, the same coil being again used and placed far out into the field, this being shown in Plate XXVI., giving a clear view of the Pike's Peak Mountain Range in the background. The diagrams and several remarks before made apply to some extent also to these three photographs which were taken after sunset when the dark began to set in, as it was impracticable to take them at another hour of the day. They might have been taken by moonlight but the time was otherwise occupied. During the hours when the light was strong it would have been necessary to exclude first the daylight in some way, flash the lamp in the dark and finally make a short exposure to the full daylight to get the detail of the apparatus. It was found impracticable to get a good photograph by flashing the lamp in full daylight as the latter was too strong and the lamp did not have enough time to impress the plate as strongly as was desirable, even if it was pushed to much higher candle power than the normal. In getting the photographs, generally about 100 throws of the switch were sufficient with the lamp being pushed considerably above the normal. When the daylight was still deemed too strong Mr. Alley helped himself by covering the lens during the short interval when the lamp was not lighted and thus regulated the effect of the daylight, keeping it down to the required value.

The *particulars* were as follows: The coil used in these three experiments was wound on a drum before referred to of 25.25" diam. and had 274 turns of wire No. 10, rubber covered. Since another coil wound on the same drum had 404 turns and an inductance of approximately 40,000,000 cm. or 0.04 henry the inductance of the present coil was with fair approximation $\left(\frac{274}{404}\right)^2 \times 0.04$ henry or $\left(\frac{137}{202}\right)^2 \times 0.04$ henry. The wire leading from the ground plate to the lower end of the coil placed on the table or ground consisted of two pieces of cord No. 10, one 308 feet and the other 84 feet long. The inductance of these two pieces of wire was estimated at 113,000 cm and compared with the inductance of the coil itself was very small, almost negligible. Calling the total inductance of the excited circuit comprising the two pieces of wire and the coil used L_1 we have for this inductance value $L_1=\left(\frac{137}{202}\right)^2 \times 40{,}000{,}000+113{,}000=18{,}400{,}000+113{,}000=18{,}513{,}000$ cm, or $L_1= =\frac{185}{10^4}$ henry. This inductance, with its distributed capacity, gave a system responding



Phot. XXVI. Experiment to illustrate the transmission of electrical energy without wire. The photograph shown is reproduced from Tesla's article[41] to the primary vibration when the capacity in the primary or exciting circuit was 1 2/3 tanks or 60 bottles on each side, or 30 bottles total, that is, $30 \times 0.0009 = 0.027$ mfd, total.

The vibrations were impressed on the ground plate by the oscillator with normal connection, that is, two primary cables in multiple or *one* primary turn, the approximate inductance of which was 56,400 cm or, say, 56,000 cm, which is close enough for the present consideration. This inductance may have been modified by the secondary, but the effect of the latter must have been very slight as, with the capacity used, it was "out of tune" and the current through it was necessarily very small. Taking then the inductance of the primary exciting circuit at 56,000 cm, the period of this circuit was

$$T_p = \frac{2\pi}{10^3}\sqrt{0.027 \times \frac{56}{10^6}}.$$

Now calling C_s the "ideal" capacity of the excited circuit, the period of the same was

$$T_s = \frac{2\pi}{10^3}\sqrt{\frac{185}{10^4} \times C_s} \text{ and equating we have } C_s = \frac{10^4}{185} \times 0.027 \times \frac{56}{10^6} = \frac{56 \times 0.027}{185 \times 10^2} \text{ mfd},$$

or $C_s = \dfrac{9 \times 10^5 \times 56 \times 0.027}{185 \times 10^2} = \dfrac{243 \times 56}{185} = \mathbf{75.2\ cm}$, approx. From above

$$T_p = \frac{2\pi}{10^3}\sqrt{0.027 \times \frac{56}{10^6}} = \frac{2\pi}{10^6}\sqrt{1.512} = \frac{6.28}{10^6} \times 1.23 = \frac{7.7244}{10^6}$$

and $n = 129{,}500$ per second nearly.

The theoretical wave length would thus be $\lambda = \dfrac{186{,}000}{130{,}000} = \dfrac{186}{130} = 1.43$ miles approx. or $\dfrac{\lambda}{4} = \dfrac{1.43}{4} = 0.3575$ miles or $0.3575 \times 5280 = 1888$ feet $= \dfrac{\lambda}{4}$.

The actual length of wire in the experiment was: 274 turns of the coil, each 79.29" = = 1810 feet + one piece of wire 304 feet + one piece of wire 84 feet = 1810 + 304 + 84 = = 2198 feet or nearly 15% more than the theoretical value. The fact is, the adjustment for resonance was not quite close as the lamp lighted could not withstand the current by closer adjustment. Two of these lamps were broken. The energy transmitted through the ground to the coil was, of course, small in this instance, since only a small part of the available primary capacity was used, that is, $\dfrac{1.66}{8}$ of the available capacity and the current of the supply transformers was reduced as far as practicable. If a coil especially adapted for the full output of the oscillator would have been used it would have been practicable to transmit many times the amount of energy needed for lighting the lamp. The lamps used in this experiment were special ones each taking, under the conditions of the experiment, perhaps 10 watts or nearly so. Assuming again a circuit under ideal conditions with the capacity of 75.2 cm on the free end of a coil without distributed capacity, and calling the potential to which this capacity would be charged P, the total energy set in movement in the excited system would be $2 \times 129{,}500 \times \frac{P^2 \times 75.2}{2 \times 9 \times 10^{11}}$ watts. If we assume that, as before, 1% of the total energy of the system is frittered down in the lamp we would have, in conformity with what was stated before for determining P, the equation

$$2 \times 129{,}500 \times \frac{P^2 \times 75.2}{2 \times 9 \times 10^{11}} = 1000 \quad \text{or} \quad P^2 = \frac{18 \times 10^{11}}{259}$$

or

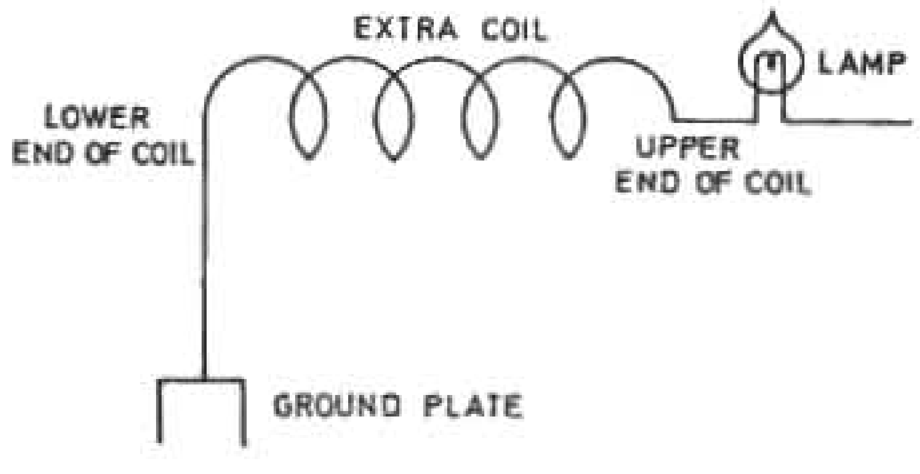
$$P = 10^5 \sqrt{\frac{180}{259}} = 10^5 \sqrt{0.695} = 10^5 \times 0.834$$

or **83,400 V** nearly, which is a small e.m.f. The length of wire in excited circuit was as before stated 2198 feet; the wire being No. 10, with a resistance of 1 ohm per one thousand feet, the resistance of the circuit was about 2.2 ohm. From above $p = 2\pi n$ was $= 6.28 \times 129{,}500 =$ $= 813{,}260$ or, say, $813{,}000 = p$. The inductance being, as shown, $\frac{185}{10^4}$ henry, the magnifying factor in the coil was $\frac{\frac{185}{10^4} \times 813 \times 10^3}{2.2} = 6840$ nearly. The lamp was one with a very short filament and its resistance may have been possibly 6 ohms. Thus with the lamp comprised the magnifying factor was still very considerable, that is, $\frac{185 \times 813}{82} =$ $= 1830$ or nearly so. Taking it at 1800 we see that it was necessary, under the conditions assumed, to impress upon the ground plate, or near portions of the ground an electromotive force of only $\frac{83{,}400}{1800} = \frac{834}{18} = 52$ volts or nearly so! This seems very little indeed, it can be scarcely believed, but the figures seem to be not far from truth. These remarks refer particularly to the experiment illustrated on the plate marked XXIV. in which the connections were the same as in the diagram shown when discussing Plate XXII., the lamp or lamps being in series with the excited coil or system.

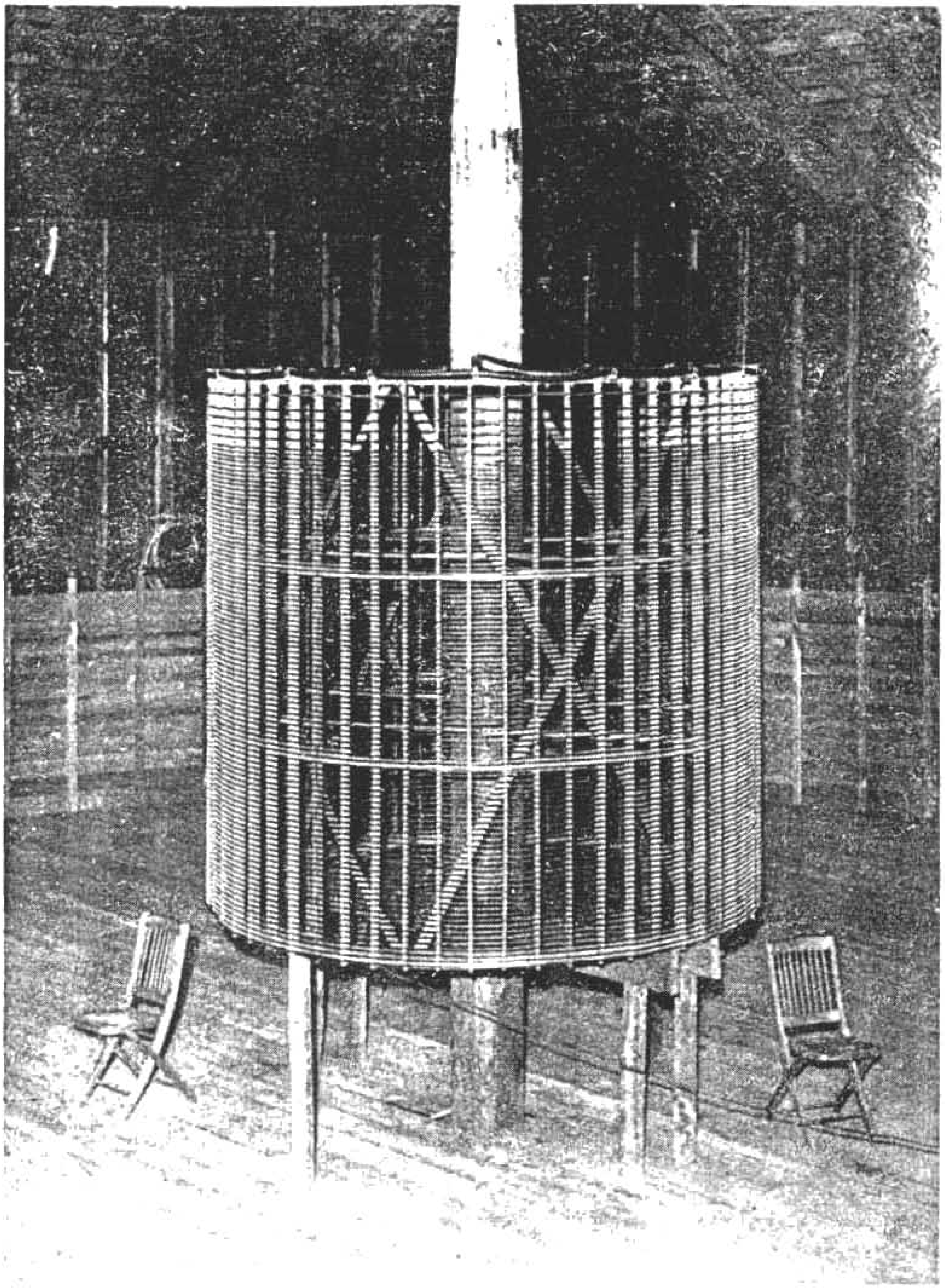
In the experiments illustrated in the Plates marked XXV. and XXVI., the connections were schematically the same as in diagram shown a propos Plate XXIII. and the vibrations and other particulars were practically the same as in experiment shown in Plate XXIV. just described. It is to be stated that when a secondary circuit is used, as in experiments described under XXIII., XXV. and XXVI., in connection with the excited coil, this secondary should for maximum effect be placed near the lower end of the coil; the exact position may be determined by experiment or approximately calculated. Namely, if the coil which is excited were devoid of capacity and the necessary capacity were all on the upper or free end of the coil, then the secondary circuit should, for maximum effect, be just at the center of the coil. But in the experiment as shown, the capacity is distributed and the current is strongest in the first or lowest turn, diminishing towards the top of the coil in each turn. The resultant maximum effect is thus always found near the lower end of the coil, but not quite at the end, since the upper turns also effect the secondary circuit, though proportionately less than the lower ones. The calculation of the maximum position of the secondary is complicated by the fact that generally neither the capacity nor the potential is uniformly distributed, the distribution being greatly varied by very slight irregularities in the dimension of the individual turns or their position, or the position of the nodal point or points on the wire and many other causes. It is proposed to investigate this subject specially when time permits.

XXVII. This photograph shows an incandescent lamp 16 c.p., 100 V connected with *one* of its terminals to the top or free end of the extra coil, the lower end of the latter being connected to the ground plate. The carbon filament is brought to incandescence by the currents transmitted from the ground plate and the rarefied gas is also glowing as evident from the photograph. It is instructive to note the great actinic power of the glowing gas which, though appearing to the eye of feeble luminosity as compared with the lamp filament, nevertheless impresses the plate at least as strongly, if not more so, than the incandescent filament.

In many experiments made a few years ago I observed this and also that certain gases are particularly adapted to impress the plate. This fact, again observed, impresses me more and more with the value of powerfully excited vacuum tubes for purposes of photography. Ultimately, by perfecting the apparatus and selecting properly the gas in the tube, we must make the photographer independent of sunlight and enable him to repeat his operations under exactly the same conditions, which is almost indispensable in order to attain the best results. Such tubes will, however, enable him to regulate the conditions and adjust the light effects at will. Such a facility would offer a very great advantage to the artist as with the sunlight, particularly in large cities where the air is not very pure, he has to rely much on chance and where it is almost impossible for him to perform two successive operations under the same conditions or to adjust beforehand the light effects. The photograph described shows also the high actinic power of streamers when they are of a bluish or violet color as frequently, which is the case in this instance. The red streamers are comparatively very slow in their action, but it should be stated that apart from the color the action on the plate is determined much by the power or intensity of the streamers. Thus with the powerful apparatus which I have perfected here the actinic rays are much more powerful than with the New York apparatus. In the experiment illustrated the results would have been the same if *both* of the terminals of the lamp would have been connected to the free end of the "extra coil" instead of only one, as illustrated in the diagram, which is added for the purpose of showing more clearly how the connections in this case were made.



Now, as to the other particulars of the experiment, the capacity in the primary or exciting circuit was 3 tanks on each side or 1 1/2 tanks total, that is 54 bottles or $54\times$ $\times 0.0009=0.0486$ mfd. As to inductance of the exciting circuit there was the primary turn with closed secondary=41,000 cm. and 5 3/4 turns of regulating coil, including connections, making an inductance, according to the table, of 17,684 cm, that is, the



Phot. XXVII. An incandescent lamp connected with one of its terminals to the top or free end of "extra coil", the lower end of the latter being connected to the ground plate total inductance of the exciting circuit was 58,684 cm, or, with fair approximation, 59,000 cm$=\frac{59}{10^6}$ henry. These data give

$$T=\frac{2\pi}{10^3}\sqrt{0.0486\times\frac{59}{10^6}}=\frac{2\pi}{10^6}\sqrt{2.8674}=\frac{6.28}{10^6}\times 1.7=\frac{10.676}{10^6}$$

and n=93,700 *approx.* and 588,000=p nearly.

If we assume, as in previous cases, that one percent of the total energy of the vibrating system is used up in the lamp in unrecoverable form, the energy of the system would then be 100 wats per each watt used in the lamp, or taking the lamp at 16 c.p. consuming, say, 50 watts the energy of the system would have to be 5000 watts. From this we get the potential P on the free end of the coil approximately by equating:

$$5000=\frac{c}{9\times 10^{11}}\times\frac{P^2\times 93{,}700\times 2}{2}$$

Here c would be the capacity of the lamp or other object, in centimeters, and taken in the same way as before explained. In previous measurements by resonance analysis the capacity of such a lamp was found to be only *1 cm*, approximately. Taking this value for c we have:

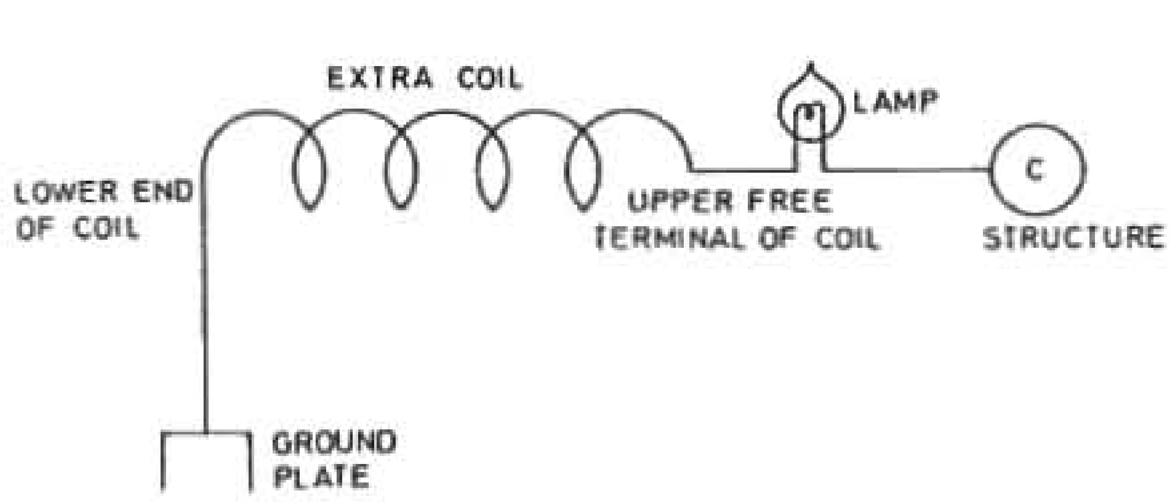
$$P^2=\frac{5\times 10^3\times 9\times 10^{11}}{937\times 10^2}=\frac{45\times 10^{12}}{937}$$

and

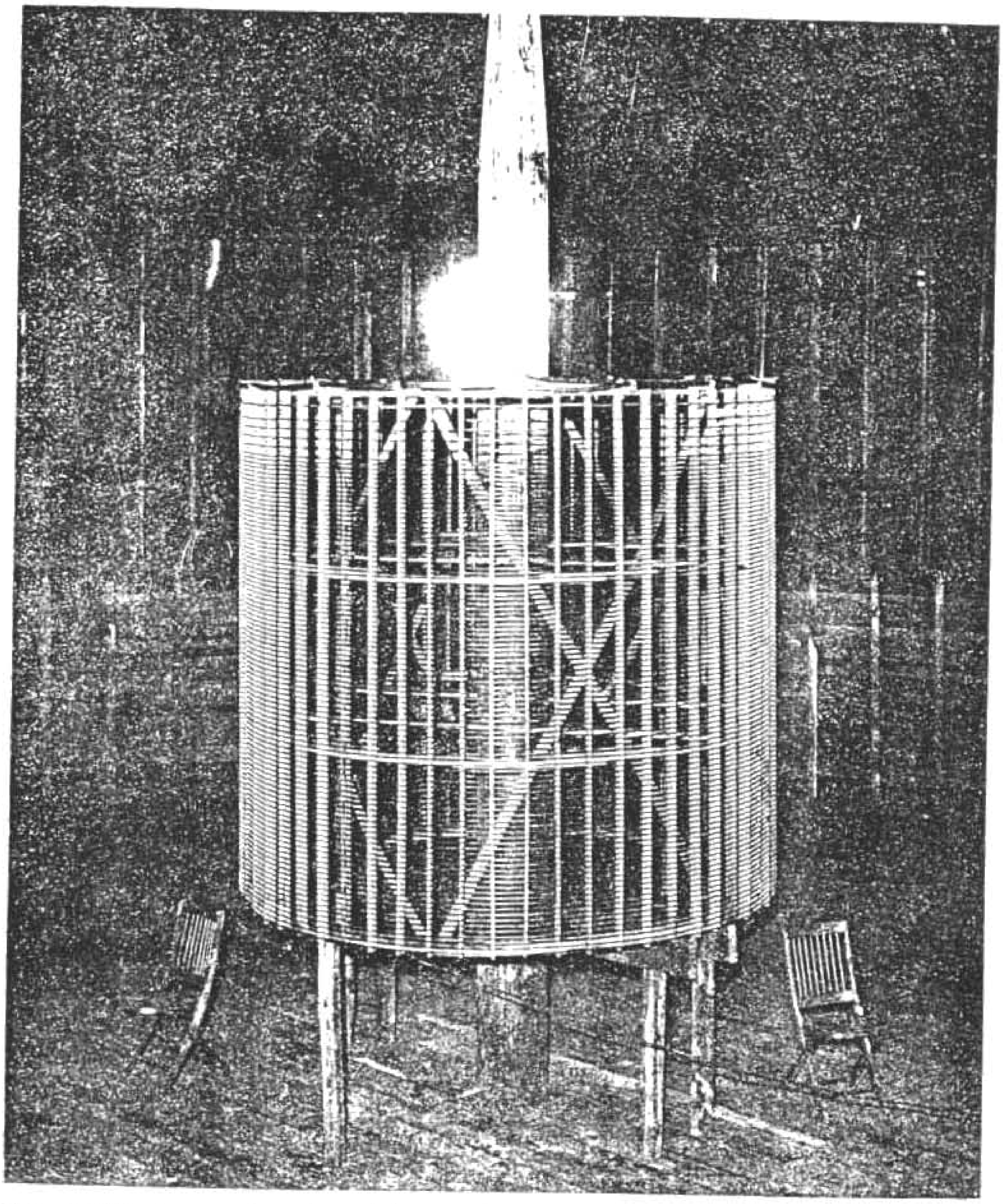
$$P=10^6\sqrt{\frac{45}{937}}=10^6\sqrt{0.048}=10^6\times 0.22$$

or = *220,000 volts*=P. This shows that P would be rather large on the assumption of but 1% frictional work in the lamp. In reality, as I know by experience, there will be generally much more energy, of the total energy of the system, used up in the lamp so that the potential P will be found in practice much smaller. But it is to be stated that *owing* to the *small capacity* of the lamp it will be relatively very high. By providing capacity in any way, so as to enable the lamp to take more energy, the potential required may be reduced at will.

This will be apparent from another photograph which is marked XXVIII. In this instance the same connections were used as before, only the free terminal of the lamp was connected by a wire to the structure of iron pipes above. The wire can be scarcely distinguished. In this experiment resonance with the exciting circuit was obtained with 6 tanks on each side, this would mean a capacity of three tanks or 108 bottles= $108\times 0.0009=0.0972$ mfd.



The inductance of the exciting circuit comprised a primary



Phot. XXVIII. An incandescent lamp lighted by the current passing from "extra coil" to the structure of iron pipes. The lower end of the coil is connected to the ground plate.

turn with secondary short-circuited=41,000 cm, as before, and *all* the turns of the regulating coil with connections, that is about 85,000 cm, giving total inductance at 41,000+85,000=126,000 cm or $=\frac{126}{10^6}$ henry. From this follows

$$T=\frac{2\pi}{10^3}\sqrt{0.0972\times\frac{126}{10^6}}=\frac{2\pi}{10^6}\sqrt{12.2472}=\frac{6.28\times 3.5}{10^6}=\frac{21.98}{10^6}$$

and

$$n=45{,}496 \text{ or approx. } \mathbf{45{,}500=n}.$$

As will be seen from the consideration of the diagram above, in this experiment the *entire* energy supplied to the structure or capacity C had to pass through the lamp. Suppose the latter to consume 50 watts, and taking the capacity C with reference to previous estimates roughly at 500 cm. with the protecting hood, and designating with P again the potential to which the structure is charged, we have

$$50=\frac{500}{9\times 10^{11}}\times\frac{P^2\times 45{,}500\times 2}{2} \text{ or } P^2=\frac{9\times 10^8}{455}$$

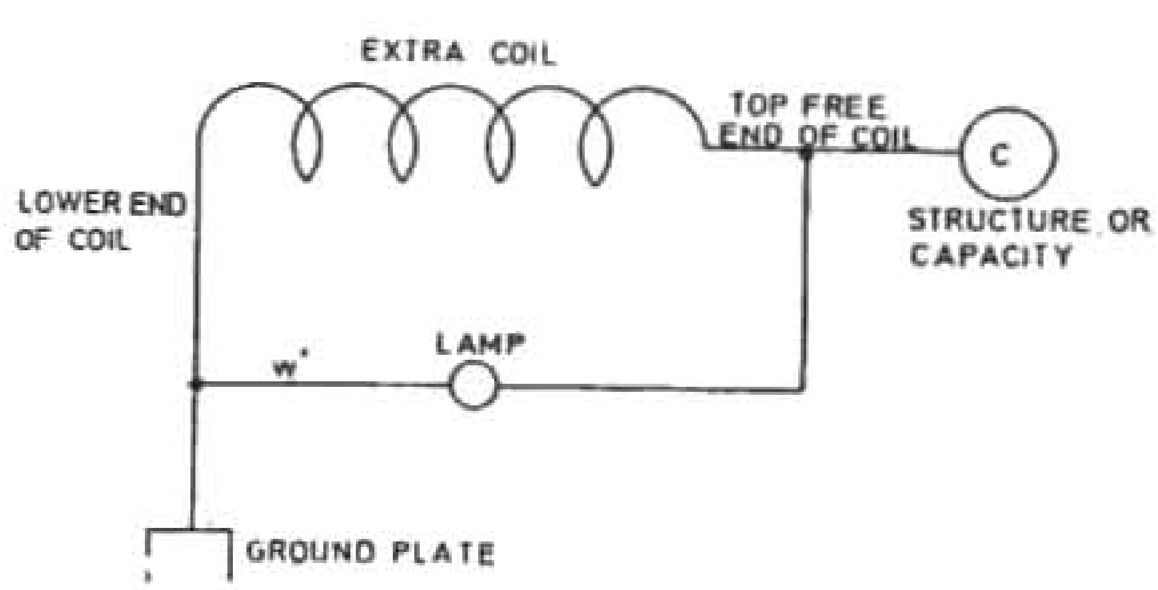
and

$$P=\frac{3\times 10^4}{\sqrt{455}}=\frac{3\times 10^4}{21.3}$$

approx. or=**1409 volts=P**, which is a very small pressure indeed. This pressure could have been, of course, still further reduced by using a resonating circuit of still higher frequency. In the manner just described and illustrated a great many lamps could have been lighted by the vibrations transmitted to the ground and some of the facts pointed out before will enable one to make an approximate estimate in this respect. However, by connecting the "extra coil" as in normal operation, that is, to the free end of the secondary instead of to the ground, a number of lamps might have been lighted corresponding to the full output of the oscillator, say, one thousand lamps or more. Even through the ground, as in the experiment described, the action of the exciting circuit was so intense that the current of the supply transformers had to be cut down to but a very small fraction of the current taken by full output.

It should be remarked that also in the experiment described before (Plate XXVII.) a considerable number of lamps might have been lighted, but not nearly as many as in the case presently described, owing to the very small capacity of the lamps, as before stated.

Coming now to the other experiments, a lamp was lighted in the manner illustrated in Plate XXIX. in which case the lamp was connected in a *shunt* to the extra coil instead of in series with the same, as in the previous case. The diagram illustrates the connections clearly. In this experiment resonance with the exciting circuit was obtained with 22 bottles on each side, that is, 11 bottles total capacity or $0.0009\times 11=$ $=0.0099$ mfd total capacity. There were 4 1/2 turns in the regulating coil of an inductance according to



the table of 13,474 cm. This, with the 41,000 cm as before, would give an approximate inductance of 54,500 cm for the exciting circuit and from this

$$T_p = \frac{2\pi}{10^3}\sqrt{0.0099 \times \frac{545}{10^7}} = \frac{2\pi}{10^6}\sqrt{0.00099 \times 545} =$$

$$= \frac{2\pi}{10^6}\sqrt{0.53955} = \frac{2\pi}{10^6} \times 0.735 = \frac{4.6158}{10^6}$$

and $n = \mathbf{217{,}000}$ per sec. approx.

As in this case the capacity may be put approximately at 500 cm, we may roughly estimate the effective inductance in the excited circuit. Namely, calling this inductance L_s we have, for the condition of resonance,

$$T_p = T_s \text{ or } \frac{2\pi}{10^3}\sqrt{0.0099 \times \frac{545}{10^7}} = \frac{2\pi}{10^3}\sqrt{\frac{500}{9 \times 10^5} L_s}$$

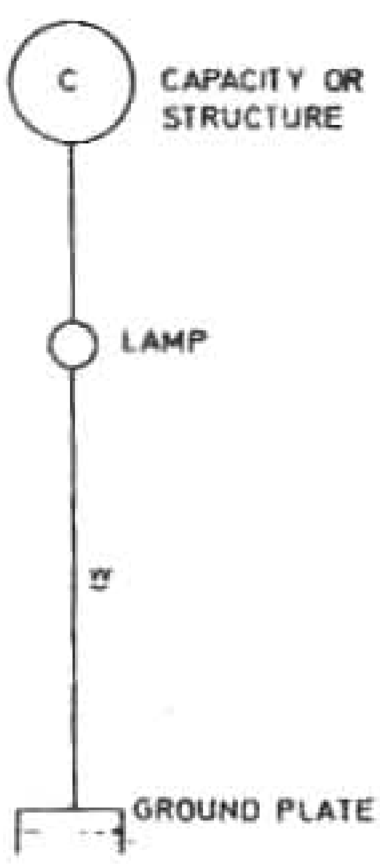
and from this

$$L_s = \frac{0.0099 \times 545 \times 9}{5 \times 10^4} = \frac{48.56}{5 \times 10^4} \text{ henry}$$

or

$$\frac{48.56 \times 10^5}{5} = \frac{4{,}856{,}000}{5} = \mathbf{971{,}200} \text{ cm.}$$

This was the effective or actual inductance, or nearly so, of the combined system of extra coil and lamp as connected in the diagram on p. 361. Evidently, in the experiment the lamp might have been lighted by doing away entirely with the extra coil and in fact I have done so. Time did not permit taking a photograph of the experiment thus modified.



In such a case, the inductance of the wire w (see diagram) need be very small, hence the frequency of the currents impressing the vibration upon the ground plate will be very high and the potential, to which the capacity C will have to be charged in order to pass enough energy through the lamp or other working circuit, will be comparatively very small. By way of example, suppose wire w, forming practically all the inductance of the excited circuit, had 10,000 cm and C were the same structure as in the experiment last described of a capacity of 500 cm; then calling P_2 the potential to which the capacity is to be charged in order to supply 50 watts to the lamp or working circuit, we would have:

$$50 = \frac{P_2^2 \times 2n}{2 \times 9 \times 10^{11}} \times 500 \text{ or } P^2 = \frac{9 \times 10^{10}}{n}.$$

Now, calling T the period, we have

$$T = \frac{2\pi}{10^3}\sqrt{\frac{10{,}000}{10^9} \times \frac{500}{9 \times 10^5}} = \frac{2\pi}{3 \times 10^7}\sqrt{5} = \frac{6.28 \times 2.236}{3 \times 10^7} = \frac{4.68}{10^7}$$

and from this

$$n = \frac{10^7}{4.68} = 2{,}137{,}000 \text{ per sec.}$$

Substituting this for n we get

$$P^2 = \frac{9 \times 10^{10}}{2{,}137{,}000} \text{ or } P^2 = \frac{9 \times 10^{10}}{214 \times 10^4} = \frac{9 \times 10^6}{214}$$

and

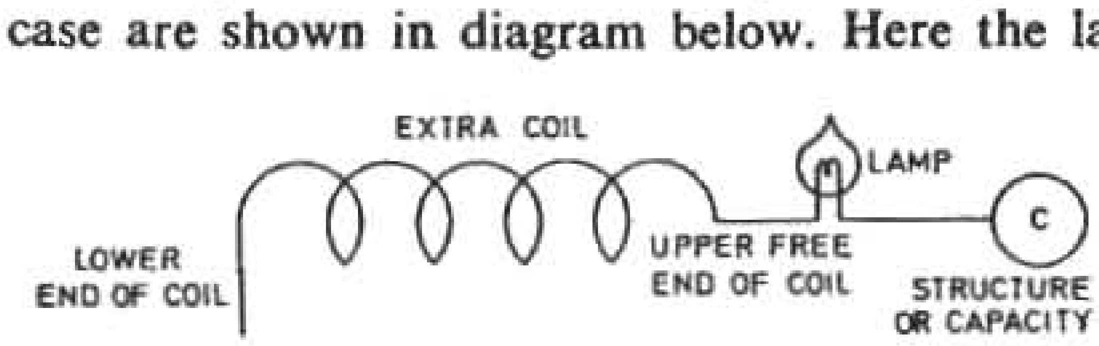
$$P=\frac{3000}{\sqrt{214}}=\frac{3000}{14.63}=\textbf{205 volts} \text{ only!}$$

We see that with such an extreme frequency the voltage of the ordinary incandescent lamp supply circuit would be sufficient to pass enough current through the lamp. Under the above conditions the current would be

$$I=EC\omega=\frac{205\times 500\times 2\pi\times 214\times 10^4}{9\times 10^{11}}=1.5313 \text{ amp. approx.}$$

In the experiment illustrated in Plate XXIX. it will be seen that while the inductance of the "extra coil" was greatly reduced by shunting the same with the lamp, yet the coil was still effective, as is evidenced from the streamers visible on the wire leading from the lower end of the coil to the lamp, which is the wire marked w' in the corresponding diagram.

Passing now to the experiment illustrated in plate designated number XXX., the connections in this case are shown in diagram below. Here the lamp was lighted only



by induction from the primary circuit, the ground connection being omitted. In this case the capacity was 3 tanks on each side or 1 1/2 tanks total=54 bottles=$54\times 0.0009=$ $=0.0486$ mfd and the inductance 41,000+3 turns of the regulating coil=$41{,}000+10{,}000=$ $=51{,}000$ cm, or $\frac{51}{10^6}$ H approx. This gives

$$T_p=\frac{2\pi}{10^3}\sqrt{0.0486\times\frac{51}{10^6}}=\frac{2\pi\times 1.37}{10^6}=\frac{8.6}{10^6}$$

and $n=116{,}300$ approx.

Note: Here the excitation of the primary circuit had to be strong, showing that the inductive action was feeble in comparison with action through the ground. The tuning was not quite exact in all these experiments described as time was pressing. In the last experiment n ought to have been just twice the value found in case XXVIII.

XXXI. This is a Roentgen photograph taken in a peculiar manner. It so happened that a workman who thought he had injured one of his figures desired to have a photograph taken and a tube was inserted between the ground plate and a coil, as illustrated in the diagram under XXII. It was doubtful whether the tube could be energized in this manner but the experiment proved that it could and a photograph was taken by flashing the tube a few times, after the adjustment of the vibration in the primary and excited circuit was completed and resonating condition in the latter secured. Nothing peculiarly interesting beyond the manner of taking the photograph was contemplated, nevertheless an inspection revealed that this photograph, probably owing to the high economy of the oscillating systems used in these experiments, or possibly on account of the frequency, was distinctly different from many others taken with different apparatus. The tube was *not strongly excited* and the exposure was scarcely more than a few seconds, yet much of detail was recorded. It is quite curious how plainly the nails are shown, much as in an ordinary photograph.

Colorado Springs laboratory fully developed.

On this occasion I must point out a peculiar feature about the action of the currents developed by this apparatus upon Roentgen tubes. As might be expected, some experiments were carried on in this line also and possibly with greater pleasure than those in other directions, for my conviction is growing stronger every day that, with apparatus such as the present, wonderful results must be secured provided only that a tube is constructed capable of taking up any amount of energy. On my return this task will be a serious one. Many times tubes have been worked here from the secondary but curiously enough, for a reason which is to me not yet clear, they can only work for a *few seconds at the most* as, almost instantly, they become very highly rarefied and the sparks begin to dart over the glass, the tube becoming useless. No matter how the current was cut down the action took place, unless it was reduced to such an extent that the tube was scarcely excited at all. Already in New York with an apparatus similar to this, though much smaller, I observed that such an action always occurs, *in some degree*, when the vibrating system possesses a very *small resistance* and the electrical movement in the circuit connected to the tube is very large. This will be further investigated.

XXXII. This is a central view through the open entrance spoiled . . .

Note: Plate XXXIII. is missing. One more photograph is to be made showing a lamp lighted without a coil, merely in series with a plate or object as capacity. If time permits a special coil will be constructed for *full power* of apparatus and all photographs, as far as practicable, taken *outside*. Taken in this manner they would be undoubtedly much more interesting to scientific men.

Colorado Springs

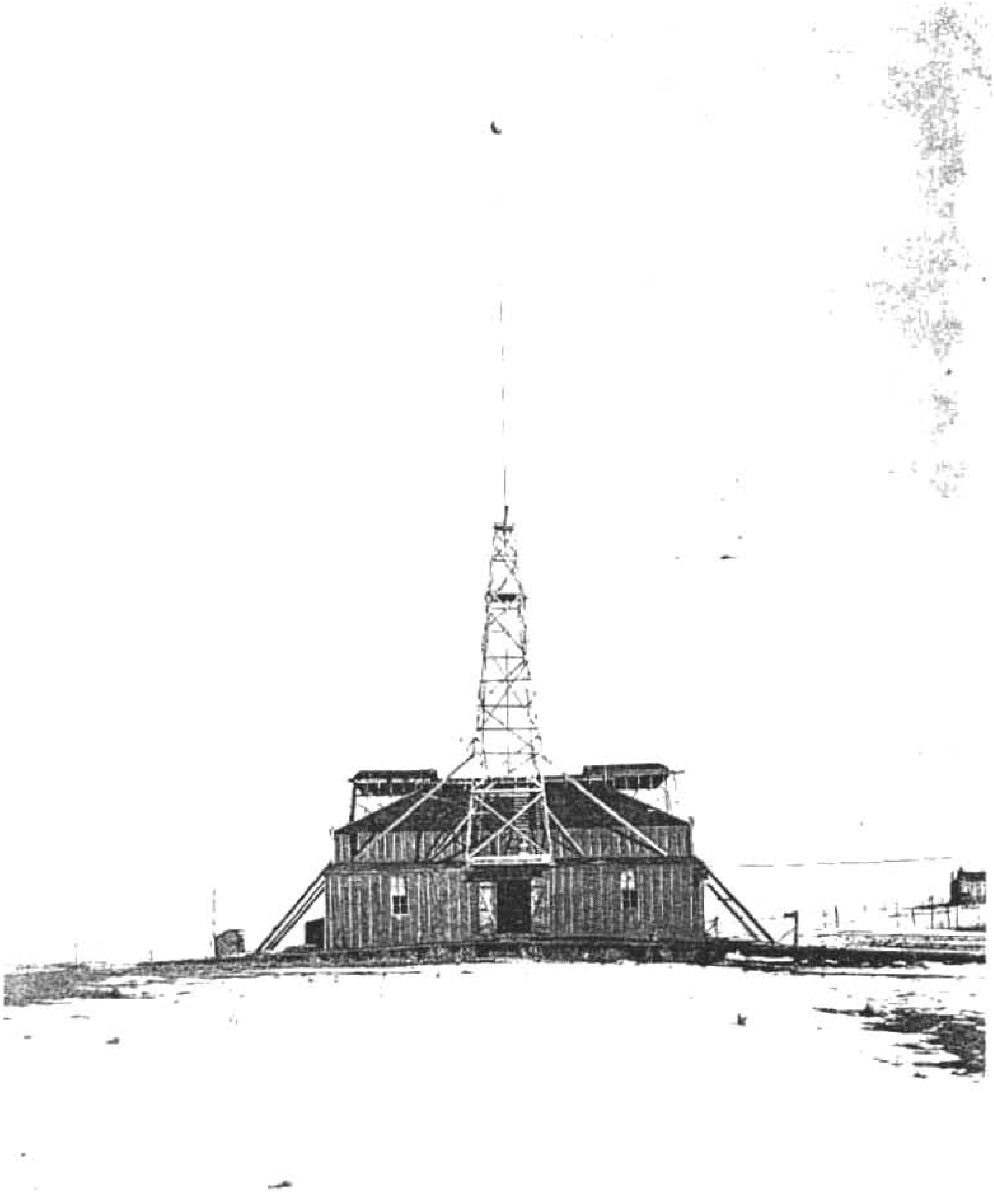
Jan. 3, 1900

Photographs taken with Mr. Alley from Dec. 17 to Dec. 31, 1899 and *particulars* relating to the same.

In the photographs, which will be presently described, 11"×14" Cramer plates were used, most of which were "instantaneous isochromatic".

XXXIII. View of the Pike's Peak Range taken from room through the window glass by moonlight, the night of an eclipse. A gale was blowing and it being impossible to place the camera outside, the photograph was taken in the above manner. As the building was trembling more or less during the sudden gusts of wind the picture is not as perfect as it might have been. The light was magnificent, the moon almost full and a good photograph might have been taken in 10—15 minutes. There was, of course, considerable loss in the transmission through the window glass though it was thoroughly cleansed, nevertheless the photograph is as good as if it had been taken in daylight. The exposure was much too long, *two hours*, from 9—11. Had the wind not been blowing a perfect picture would have been obtained in a quarter of that time. The wonderful brightness of the moonlight was increased by the snow which was unusually heavy.

XXXIV. This photograph shows the laboratory viewed from behind with the mountain range from Pike's Peak to Cheyenne Mountain in the background. There was



Phot. XXXVIII. View of the laboratory from the Pike's Peak side.

not much snow on the ground and little or none on the roof. The exposure was only 35 minutes, the moon nearly full. As the wind was blowing, the ball on top of the pole does not show well.

XXXV. This is another view of the laboratory from the rear with the Pike's Peak Range as background. Considerable snow on the ground. The exposure was *two hours.* It was again a windy night and the image of the upper part of the pole and ball is marred owing to swaying.

XXXVI. Again a view of the laboratory from the rear with the lower mountain range on the right side of Pike's Peak as background. There was snow on the ground. Extremely cold and very windy. Exposure 40 *minutes.*

XXXVII. Once more a view of the laboratory from the rear with the Pike's Peak Range as background. The moon was waning and a longer exposure — *three hours* — was made. It was found that the plate was somewhat over-exposed. Otherwise the conditions were not unfavourable. The wind was not strong and there was still considerable snow on the ground. The above photographs satisfied fully the novel pleasure of taking pictures by the fascinating moonlight of Colorado and attention was then turned to less agreeable but more useful work.

XXXVIII. This is a view of the laboratory from the Pike's Peak side taken in the morning by sunlight, fresh fallen snow on ground.

XXXIX. A view of the laboratory from the rear taken under the same conditions.

XL. Illustrates discharge of "extra coil" laterally across the field from a pointed wire on the top of the coil to a ball 30" diam., provided with a point and a coil on a stand which supports the ball. Strong streamers and sparks, the latter passing to the floor; the coil mentioned and hood fastened to structure of iron pipes in the center of the building. Some sparks passed also to the roof causing, as usual, considerable concern, the fireproof paint notwithstanding. Some streamers in the same positions as others relative to the camera are very weak, this is probably due to their red color. Many streamers show clearly the phenomenon of splitting up or ramification and the sparks, where they strike the floor, develop increased luminosity. The feature of "splashing" on the floor upon striking the same is also well illustrated, particularly on one of the streamers which is thinner and sharper than most others. To give an idea of the magnitude of the discharge the experimenter is sitting slightly behind the "extra coil". I did not like this idea but some people find such photographs interesting. Of course, the discharge was not playing when the experimenter was photographed, as might be imagined! The streamers were first impressed upon the plate in dark or feeble light, then the experimenter placed himself on the chair and an exposure to arc light was made and, finally, to bring out the features and other detail, a small flash powder was set off. It was found necessary to sit in the chair during the exposure to arc light as, otherwise, the structure of the chair would show through the body of the person, if the same were exposed merely to the light of the flash powder. As the weather during these experiments, which were carried on late at night, was most generally far below zero, I tried to overcome the above necessity but neither I nor Mr. Alley could device a practical remedy.

The simplest remedy would have been to employ a very powerful light enabling an instantaneous exposure, but this was not practicable with the arc light. On the other hand, the ball being very large, a great quantity of flash powder was required which it was not advisable to use because of danger and impairment of the quality of the photographs. In the instance described, the streamers shown were produced by 50 closures of the circuit energizing the Westinghouse transformer, each closure lasting approximately one half of one second, possibly less. The exposure to arc light lasted 5 minutes, about half of the full lens opening, and in flashing about one third of a large size Eastman powder was set off.

XLI. This is a similar view of the discharge (fifty flashes, very short) of the extra coil from a pointed wire on top, or free terminal. The photograph shows, in an interesting manner, the splitting up of streamers or sparks near the floor. Another curious feature observable is the splitting and again uniting of a streamer or spark. I say "streamer or spark" because the former becomes a "spark" or perhaps stated better, an "arc" when it strikes some object which causes a strong current to pass through the path of the streamer, which then suddenly assumes the brilliancy and color characteristic of "sparks". I have seen at times a very strong discharge dart out from a point or surface in the form of a spark, continue for 6—10 feet or so and then split up in streamers. It is more than likely that this phenomenon will be found recorded in some of the photographs taken on closer inspection, as it is not unfrequent. At times, again, I have observed a small length of a streamer, anywhere along its path, assume a relatively very considerable luminosity and assume in this part the character of a spark. This I have, if I am not mistaken, already pointed out elsewhere. Some such luminous parts or points are to be seen plainly in this and other photographs.

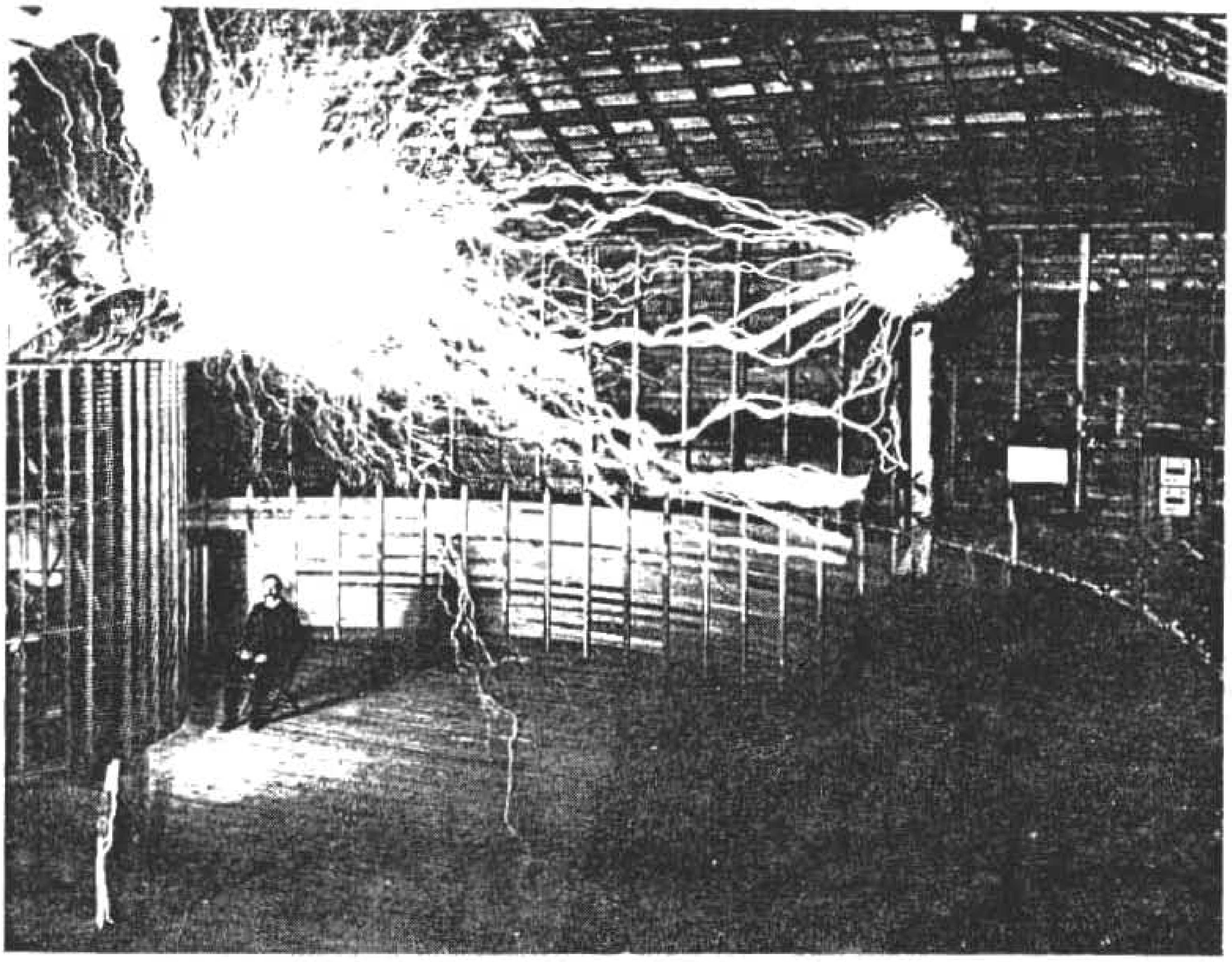
When the action is very energetic, owing to the power of the streamer and other causes, the luminous portion of the same becomes a veritable "fireball". This observation which, to my greatest astonishment, I have frequently observed in experiments with this apparatus, shows now clearly how "fireballs" are produced in lightning discharges and their nature is now quite plain. I have heretofore always been inclined to believe this phenomenon to be merely a visual impression, similar to one which is experienced upon a violent blow on the eye, or some part of the head, or the spine, or which follows upon a sudden and very intense manifestation of light most generally. Although the vision of a moving ball of great luminosity is experienced only in the rarest instances, the person as a rule seeing luminous spots, "stars" or flaming tongues.

With the present experiences I am satisfied that the phenomenon of the "fireball" is produced by the sudden heating, to high incandescence, of a mass of air or other gas as the case may be, by the passage of a powerful discharge. There are many ways or less plausible in which a mass of air might be thus affected by the spark discharge, but I hold the following explanation of the mode of production of the "ball" as being, most likely of all others which I have considered, the true one. When sudden and very powerful discharges pass through the air, the tremendous expansion of some portions of the latter and subsequent rapid cooling and condensation gives rise to the creation of partial vacua in the places of greatest development of heat. These vacuous spaces, owing to the properties of the gas, are most likely to assume the shape of hollow spheres when, upon cooling, the air from all around rushes in to fill the "cavity" created by the explosive dilatation and subsequent contraction. Suppose now that this result would have been produced by one spark or streamer discharge and that now a second discharge, and possible many more, follows in the path of the first. What will happen? Before answering the question we must remember that, contrary to existing popular notions, the currents passing through the air have the strength of many hundreds and even thousands of amperes.

It was a revelation to myself to find that, even with the apparatus used in these experiments, a single powerful streamer, breaking out from a well insulated terminal, may easily convey a current of several hundred amperes! The general impression, if I am not mistaken, is that the current in such a streamer is small but this belief is due to the comparative unfamiliarity of the electrician with such apparatus as I am now using. As a matter of fact it is quite easy to consume in such streamers, as are illustrated in these photographs, most of the energy developed by the apparatus and the currents conveyed through the air may be, by suitable provisions, made as strong as those circulating in the wire or coil itself which produces them. No wonder then, that a small mass of air is "exploded" with an effect similar to that of a bombshell, as noted in many lightning discharges.

But to return now to the explanation of the "fireball", let us now assume that such a powerful streamer or spark discharge, in its passage through the air, happens to come upon a vacuous sphere or space formed in the manner described. This space, containing gas highly rarefied, may be just in the act of contracting, at any rate, the intense current, passing through the rarefied gas suddenly raises the same to an extremely high temperature, all the higher as the mass of the gas is very small. But although the gas may have been brought to vivid incandescence, yet its pressure may not be very great. If, upon the sudden passage of the discharge, the pressure of the heated air exceeds that of the air around, the luminous ball or space will expand, but most generally it may not do so. For assume, for instance, that the air in the "vacuous" space was at one hundredth say, of its normal pressure, which might well be the case, then, since the pressure in the space would be as the absolute temperature of the gas within, it would require a temperature which seems scarcely realizable, to raise the pressure of the rarefied gas to the normal air pressure. It is therefore reasonable to expect that, despite the high incandescence of the rarefied air, the space filled with the same will continue to contract, and here an important consideration presents itself. When, as before explained, the vacuous space was formed, the spark or streamer passed through the air *disruptively*, therefore the path was necessarily very thin, threadlike, and the minute quantity of the air which served as a conductor for the current was expanded with explosive violence to many thousand times its original volume. Owing to the fact, however, that the quantity of matter through which the current was conveyed was small, a great facility was offered for giving off the heat so that the highly expanded gas-owing to its expansion and to radiation and convection of heat-cooled instantly.

But how is it when the second discharge and possibly many subsequent ones pass through the rarefied gas? These discharges find the gas already expanded and in a condition to take up much more energy by reason of the properties it acquires through rarefaction. Evidently, the energy consumption in any given part of the path of the streamer or spark discharge is, under otherwise the same conditions, proportionate to the resistance of that part of the path; and since, after the gas has once broken down, the resistance of other parts of the path of the discharge is much smaller than that including the vacuous space, a comparatively very great energy consumption must necessarily take place in this portion of the current path. Here, then, is a mass of gas heated to high incandescence suddenly but not, as before, in a condition to give up heat rapidly. It can not cool down rapidly by expansion, as when the vacuous space was being formed, nor can it give off much heat by convection. To some extent even radiation is diminished. On the contrary, despite the high temperature, it is compelled to confinement in a limited space which is continuously shrinking instead of expanding. All these causes cooperate in maintaining, for a comparatively long period of time, the gas confined in this space at an elevated temperature, in a state of high incandescence, in the case under consideration. Thus, it is that the phenomenon of the "ball" is produced and the same made to persist for a perceptible fraction or interval of time. As might be expected, the incandescent mass of gas in a medium violently agitated, could not possibly remain in the same place but will be, as a rule, carried, in some direction or other, by the currents of the air. Upon little reflection, however, we are led to the conclusion that the ball or incandescent mass, of whatever shape it be, will always move from the place where an explosion occured *first*, to some place where such an explosion occured *later*. This will be most generally in the path of the discharge, from its origin to its end, but not necessarily always so. For example, it may so happen that a spark produced in some place strikes an object of a material which is evaporated or volatilized with difficulty, and that *later*, in another place, this same or other spark hits an object of a material more volatile. If so then the explosion on the later place will sooner occur, and the result will be that the current of air, when both the explosions have subsided, will move from the later to the former locality. But I believe that, in most cases, the current of air will take the opposite course, as before stated. In whatever direction the movement may occur, it is plain that the velocity can not be very great. In fact, all observers concur in the opinion that such a "fireball" moves slowly. If we interpret the nature of this wonderful phenomenon in this manner, we shall find it quite natural that when such a ball encounters in its course an object, as a piece of organic matter for instance, it will raise the same to a high temperature, thus liberating suddenly a great quantity of gas by evaporating or volatilizing the substance with the result of being itself dissipated or "exploded". Obviously, also, it may be expected that the conducting mass of the "ball" originated as described, and moving through a highly insulating medium, will be likely to be highly electrified, which accords with many of the observations made. A better knowledge of this phenomenon will be obtained by following up experiments with still more powerful apparatus which is in a large measure already settled upon and will be constructed as soon as time and means will permit. There may be a way, however, of intensifying in this respect, the action of the present machine. A very important matter is to use better means of photographing the streamers exhibiting these phenomena. Much more sensitive plates ought to be prepared and experimented with. The coloring of the films before suggested might also be helpful in leading up to some valuable observation. It being a fact that this phenomenon may now be artificially produced, it will not be difficult to learn more of its nature. Photography will be, of course, the best means to investigate it and the first efforts ought to be in this direction. With the present plates, although the "balls" produced with the apparatus experimented with are probably up to 1 1/2" diam. and possibly more, they leave only a small dark spot on the plate, only the nucleus or central portion impressing itself.



Phot. XLIII The discharge of "extra coil" laterally across the shop. Mr. Alley is sitting.

Colorado Springs

Jan. 4, 1900

Photographs taken with Mr. Alley from Dec. 17 to Dec. 31, 1899 and *particulars* about the same:

XLII. Illustrates a similar view of same apparatus in action. The streamers and sparks are produced by 25 short throws of the switch. The sparks pass to hood, floor and roof. The "splashing" on the floor is plainly visible. Many other features of interest, some of which have been already described, may be observed in the photograph. So, for instance, one or two streamers show clearly the phenomenon, which has been dwelt upon already, namely more luminous spots or "balls". The loss in luminosity of a streamer branching out is also illustrated. To give an idea of the magnitude of the display again a human figure is introduced, this time Mr. Alley sitting. The exposure to arc light was 5 minutes, about half opening of full lens and afterward about one half of the large Eastman powder was set off.

XLIII. This shows again the same discharge laterally across the shop, as before. The sparks are more powerful this time and there are more of them, fifty throws of the switch being made. The sparks and streamers are made to issue this time from a curved wire forming the terminal of the extra coil. The sparks to the hood and to the roof are particularly interesting. The point used before on the ball 30" diam. was taken off. The extra coil unfortunately broke through some places and also to the floor.

Some of the streamers form actual loops turning back upon themselves. A curious feature is presented by a long streamer striking the wooden support of the ball and splashing from there upon the ground wire leading from the ball. Some streamers are seen to pass along the wire without striking the same, lighting finally on the ball. This plainly illustrates that the path of such a discharge is accidental, dependent on the arrangement of particles floating in the air on the currents in the latter. Luminous points are again observed on some of the streamers, as in previous instances. In this experiment the other particulars were the same as before. Mr. Alley was photographed once more, a flash being used after the arc light exposure as in the preceding case.

XLIV. This plate shows the extra coil discharging laterally across the shop and to the floor, the streamers and sparks issuing from several thin wires tied together and spread apart on the end. In this experiment several discharges to the floor were so powerful as to actually inflame the wood on the spot where they struck the wood. Several instances of "splashing" on the wood are observed. The splitting or branching is nicely shown in one of the streamers. One of the sparks strikes the wood and disappears emerging again at some distance from the spot, having evidently followed a better conducting path through the wood. A powerful spark passes to the coil on the stand, jumps out and strikes the top wire of the secondary, instead of taking the shorter and easier route along the wire to the ground. Some very curious curves and twists are observed on a number of the sparks and streamers. In the experiment, 100 throws of the switch were made and the particulars were in other respects the same as before, the vibration of the "extra coil" being the normal or nearly so.

XLV. This shows a slightly different view, the discharge of the extra coil taking a similar course laterally across the shop. Strong sparks pass to hood, floor, high coil on stand and also to roof. The photograph presents features of interest similar to the foregoing. One of the streamers behaves curiously, going for some distance away from the coil and then turning back upon the same. The feature of the thickening of some sparks and streamers on the lower end near the floor is well shown in a few instances, and unmistakably. The discharges are long as they are made to issue from the tip of a wire, mostly the leaks on other points being comparatively small. The glow of the top wire of the secondary is strong. Fifty throws of the switch were made in this instance, other particulars remaining substantially the same.

XLVI. In this case again the extra coil discharges laterally as in a number of instances just described. As there was a bad leak on a spot of the rubber cable forming the last two or top turns of the extra coil, a ball of 30" diam. was connected to the cable at that point, the object being to take up the pressure and prevent the leak. It was expected that the discharge from the end of the wire, from where it was intended to issue, would thus be strengthened. This proved to be the case decidedly, but the presence of the ball slowed down the vibration of the extra coil to some extent, thus destroying the best condition for resonance obtainable with the apparatus, for some inductance had to be inserted in series with the primary of the oscillator and this meant a slightly decreased economy. Some streamers, issuing from the large ball, despite the drain on the end of the wire, illustrate clearly the immense electromotive force and great quantity of electrical movement in the system. Many strong sparks pass to the high coil and still many more to the ground through the wooden floor, the latter showing some of the interesting phenomena described before. Particularly clear is the action of some sparks in inflaming or volatilizing the wood on the spot where they strike it. The splashing over the surface of the wood is also well shown in a number of instances. A portion of the floor struck by a number of sparks near together is considerably illuminated, chiefly by the increased light of the sparks on the surface of the floor and near the same. This additional light is, as may be seen during the experiment and also by an inspection of the photograph, due to the momentary ignition of the material to which also the thickening of the sparks near the floor might be ascribed, observable in some of the sparks. A curious screw movement is noticeable on some of the streamers. There were again 100 throws of the switch made in this experiment, the other particulars being, as nearly as practicable, the same as before.

XLVII. Once more a similar view was taken, illustrated on this plate, but the ball was not connected to the top of the extra coil and the vibration of the latter was very nearly the normal. There are some leaks on the cable on top, despite the most careful wrapping with mica and rubber, neverthelles some of the sparks and streamers issuing from the tip of the wire attain great length. A number of the sparks fly in curiously curved paths to the top wire of the secondary. These are about 22 feet or more in a straight line. There is a draught created by the discharge, as is evident from the splitting up of some sparks or streamers in individual discharges effected by the operation of the break wheel. Many interesting formations of the streamers and some phenomena before described are again noted in this case. Some sparks are seen to continue along the floor. The sparks to the hood show clearly and beautifully the effect of the draught created in consequence of the rapid heating of the air. A curious feature is afforded by some streamers actually doubling upon themselves. The secondary resonates very strongly but the strong streamers on the top wire are partially due to the reaction of the excited system. In the present instance also, 100 throws of the switch were made, the other conditions remaining practically the same as before.

XLVIII. This plate shows one of the strongest discharges viewed similarly, as in the previous cases just dwelt upon. The streamers and spark issue again from the tip of the "free terminal" wire of the extra coil. Some of the sparks pass again in winding paths, which are very long, much longer than the straight course which they should take, to the top of the secondary. These paths have easily a length of some fifty feet or so and are of extreme brilliancy. This is partially due to the capacity of the ball of 30" diam. connected to the top turn of the extra coil. Some very brilliant and thick sparks pass from the ball to the hood above and others much longer, though less brilliant, strike the high coil on the stand across the laboratory. One of the streamers is wonderfully interesting on account of the curiously twisted and curved appearance. It is hard to conceive how a discharge can pass through the air in this way when there exists a strong tendency to make it take the shortest route.

The curiously curved path clearly shows how extremely sensitive discharges of great length, and particularly those passing out into the air from a single terminal, are to currents of the air. This sensitiveness is still further increased when the streamer or spark is not compelled to issue always from the same point or points, as when the terminal is constituted by a pointed wire, but can issue with *equal facility* from other points as, for example, when the terminal is constituted by a large ball or disk. The slightest draught is, in such a case, sufficient to alter the position and shape of the streamer. In such an instance the discharge is also highly sensitive to other influences, as magnetic or electric actions, Roentgen rays, light and other forces or disturbances in the medium.

I now understand better why a "rotating brush", which I have described some years ago, is so wonderfully sensitive, many times more than any other sensitive device of which I have knowledge at present. It seems to me that a sensitive device in telegraphy on this principle will have to be ultimately adopted in preferance to others. The trouble is that it is dificult, or at any rate inconvenient, to produce and maintain the phenomenon but this difficulty may be overcome in time. The photograph described shows very beautifully how a streamer falls apart and spatters after striking a wooden structure, owing to the sudden heat evolution and gas generation at that spot. The photograph conveys well the idea of the fierceness of the discharge produced by 100 throws of the switch, other particulars remaining.

Colorado Springs

Jan. 5, 1900

Photographs taken with Mr. Alley from Dec. 17 to Dec. 31, 1899 and *particulars* about the same continued:

XLIX. This plate shows again the extra coil viewed centrally and discharging from the brass ring on top, mentioned before, to which thin wires, pointing upwards, are fastened. As the streamers are made to issue from great many points at once, they are decidedly weaker than when, as in some previous cases, permitted to issue only from a few points. This is evident from the fineness of their texture, as shown in the photograph. But the total amount of energy spent upon the air is very great in this experiment and the coil in action produces the effect of a hot furnace, creating a strong current of air through the open roof which, rushing upward, takes effect upon the streamers as is plainly recorded on the plate, particularly on the upper streamers. A very interesting long spark passes to the wire leading from the secondary. It is evident that many streamers are split up to such an extent that they do not impress the film sufficiently. In the experiment also 100 throws of the switch were made and the other particulars were nearly the same as before. The e.m.f. at the terminals of the extra coil system is necessarily smaller because of the facility afforded for the escape of the streamers and great frictional loss in the air, which causes the free oscillations of the system to die out more quickly than in some of the foregoing experiments.

L. This photograph represents a similar view of the extra coil discharging from the brass ring and wires fastened to same; in this case the wires being directed downwards The streamers show much the same character as before and many are evidently not strong enough to record their path on the film, on account of the great quantity of them. Most of them produce the effect of a strong glow only. Some strong sparks pass occasionally to the wire leading from the secondary. Again, the photograph was produced by 100 closures of the switch and normal excitation of the extra coil system.

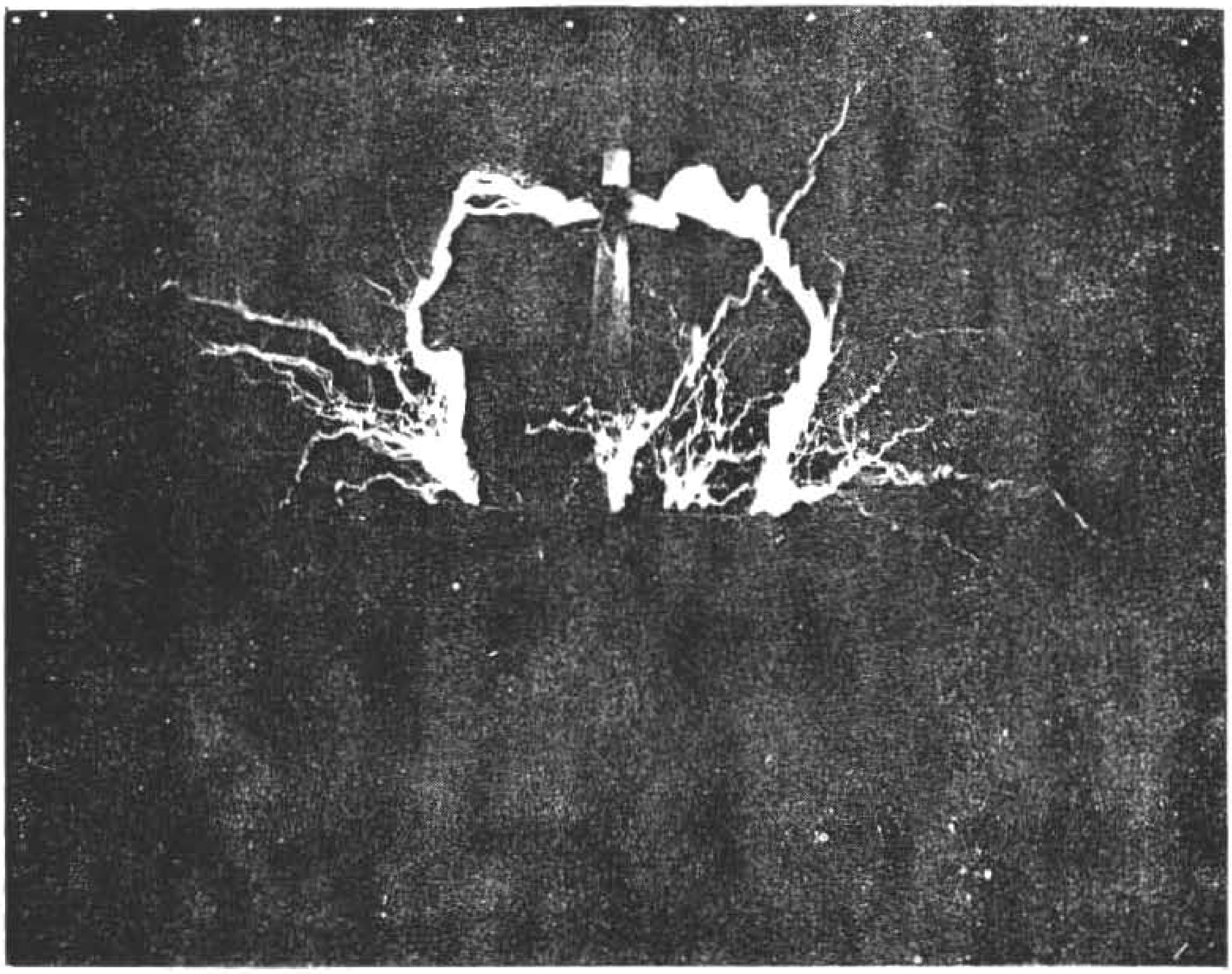
LI. This is once more the extra coil discharging under similar conditions and viewed in the same manner. The wires fastened to the brass ring forming the last turn of extra coil are in this case pointed still more downwards. To strengthen the streamers somewhat the number of the discharging wires is reduced. The streamers on the top part of the picture are very beautiful, their paths being curiously curved. But the fine texture of the discharge again shows the weakening effect of the many wires or points of issue, though the individual discharges are evidently stronger than before. Some sparks passing to the hood and floor are interesting and show that the e.m.f. has been increased by reducing the number of the discharging wires. In fact some sparks and streamers attain great length and there are a number of instances of their splitting up in curious ways illustrated. A strong draught effect is also apparent. The photograph is rendered more beautiful by its symmetry. *All particulars* remained as before.

Colorado Springs

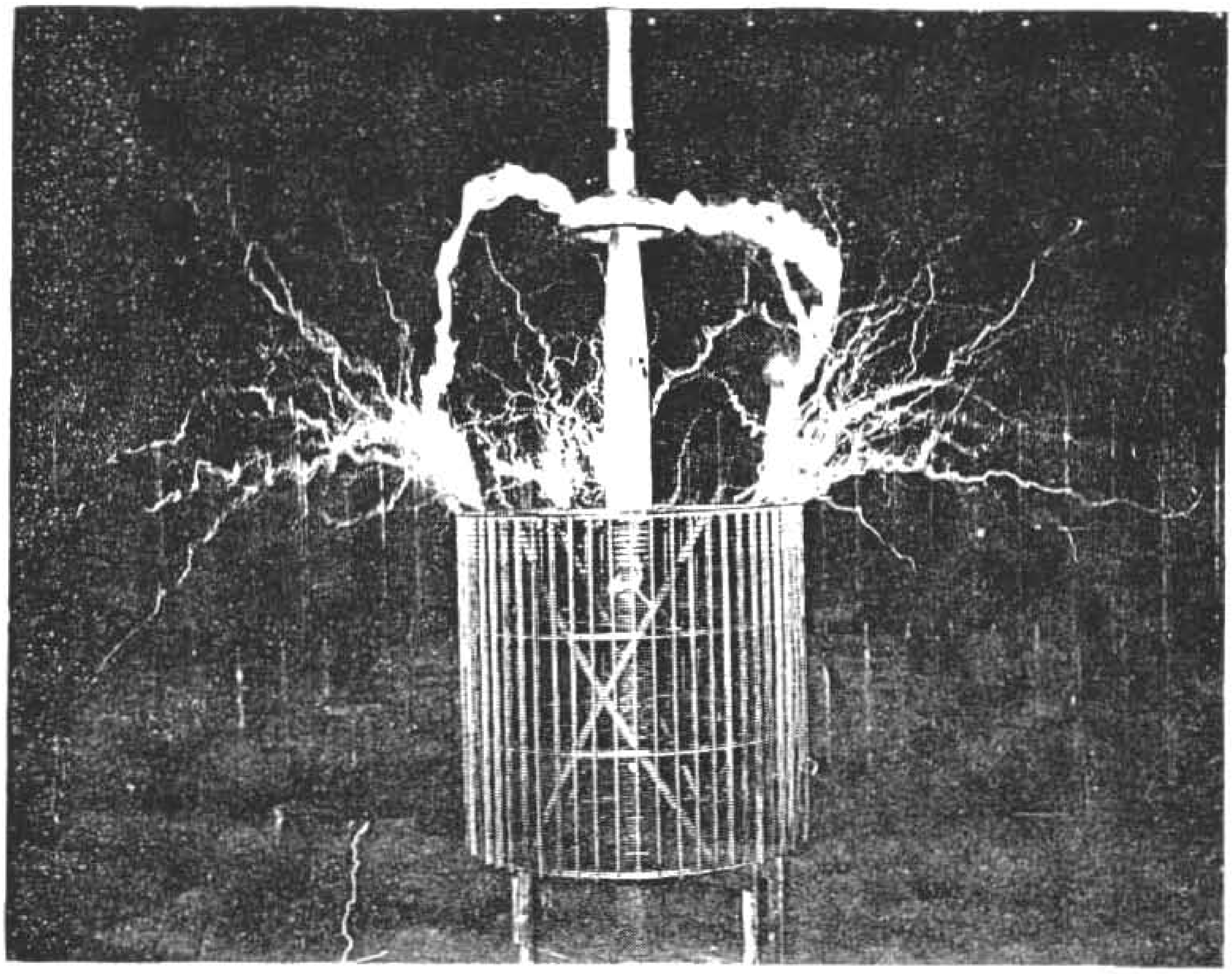
Jan. 6, 1900

Photographs taken with Mr. Alley from Dec. 17 to Dec. 31, 1899 and *particulars* relating to the same continued:

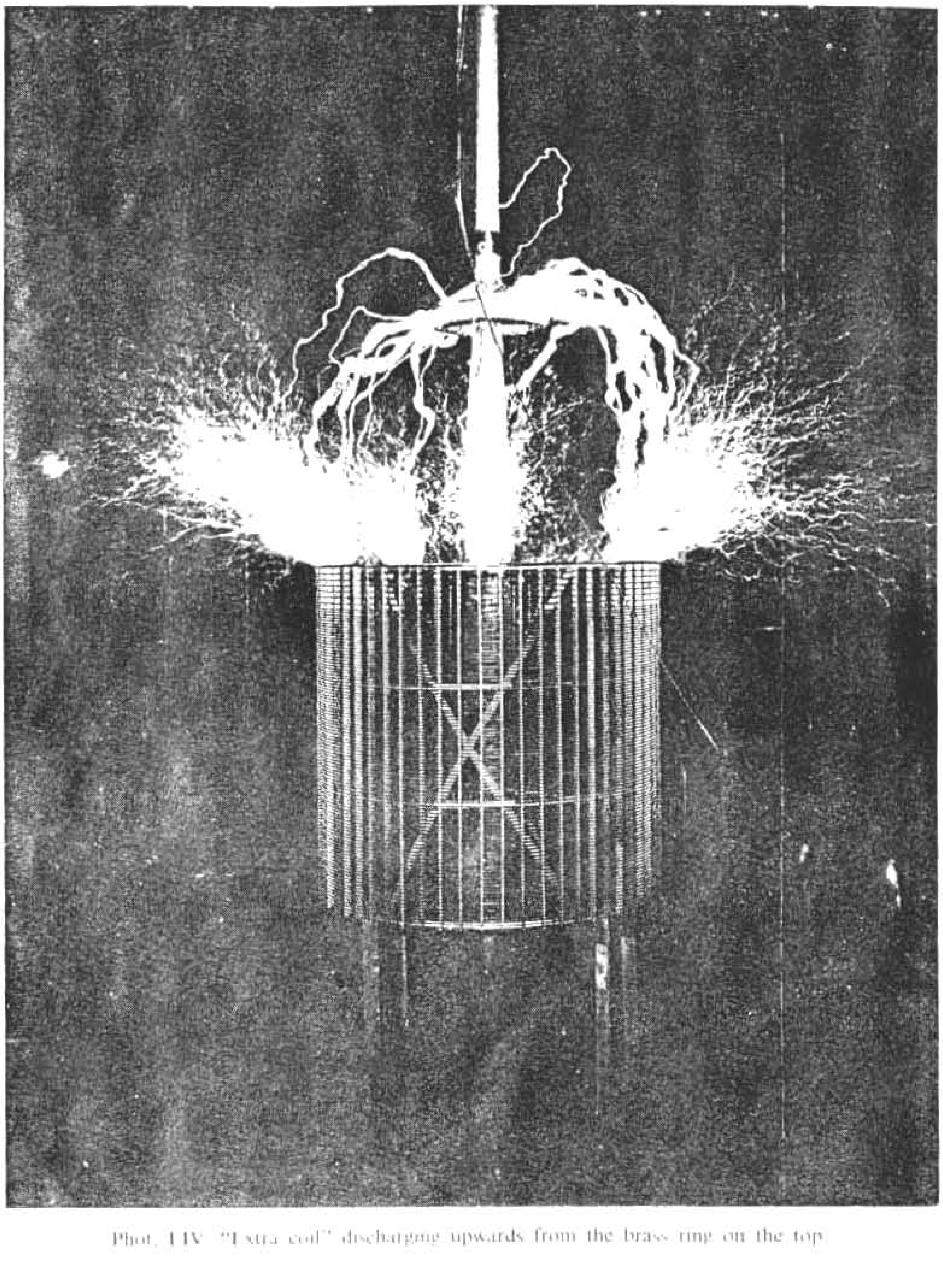
LII. This plate shows a discharge from the top of the extra coil, produced by a single closure of the circuit or throw of the switch, of very short duration. The discharge issues again from the brass ring on the top of the extra coil, which is viewed centrally. Some streamers pass into the air and sparks dart to the hood above the coil. A curious spiral or screw motion in one or two streamers is noticeable. The light of the discharge, though lasting but one fraction of a second, is strong enough to reveal a part of the structure and the top of the coil. The current of air separates the sparks and streamers into the individual discharges produced by the break wheel. This effect is beautifully shown. The vibra-



Phot. III. Discharge from the top of "extra coil", produced by a single closure of the circuit of very short duration



Phot. LIII. Produced under similar conditions as phot. LII by a single closure of the circuit but of longer duration



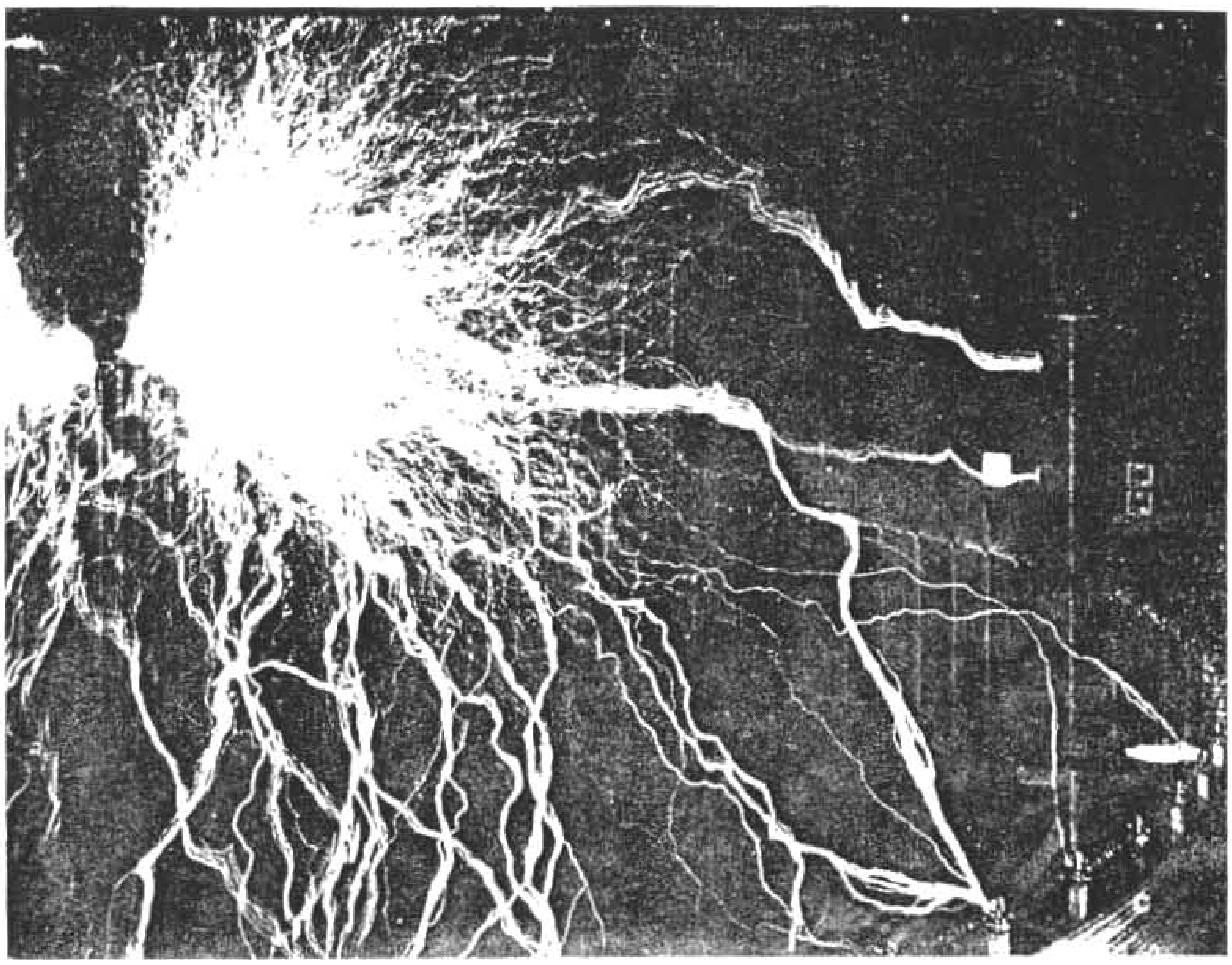
Phot. LIV "Extra coil" discharging upwards from the brass ring on the top tion of the coil and all other particulars are as in most previous instances recently described. *No* after illumination by arc or flash.

LIII. This illustrates again the discharge of the extra coil under similar conditions as produced by a single closure of the circuit through the switch, but of longer duration. This is a side piece to Photograph VI already described, only the door was not open as in that case and the draught was consequently much smaller. Some very interesting bending upon themselves and twisting of the streamers and sparks may be observed in the picture. In places, some streamers are actually interrupted. This singular phenomenon has already been described on a previous occasion. Some streamers again appear exceptionally thin though they ought to appear as thick as the others, judging from their position relative to the camera. This is evidently due to the smaller actinic power of these particular discharges, owing to which only the central and white portion impresses itself upon the film. A spark striking the floor shows the feature of "splashing", dwelt upon before very clearly. A few sparks reach the roof but do not continue along the same, being rather weak at that distance. The photograph is on the whole very beautiful. All the particulars were as normally or nearly so.

LIV. In this photograph the "extra coil" is again shown in central view discharging upwards from the brass ring or turn on the top, under conditions nearly normal. 100 throws of switch were made in the experiment. The plate is very interesting on account of the exceptional fineness of the streamers and perhaps still more so owing to the curious curves of the sparks. One of the latter is seen to pass quite close to the hood without striking it, preferring a point of the iron pole far above the hood. Another feature of interest is afforded by a streamer passing close to the iron pole and escaping through the opening in the roof, seemingly not being affected by the presence of the pole. These two discharges are very long, the latter particularly. The photograph is very successful, the focusing being excellent.

LV. This plate illustrates the discharge passing laterally across the laboratory from the tip of a wire, forming the "free" terminal of the extra coil, chiefly to the floor and top wire of the secondary. The sparks and streamers are very powerful and long, exhibiting many of the phenomena described in some cases before. One spark passing from the terminal of the extra coil across the laboratory is of rare beauty showing the individual discharges effected by the break wheel exceptionally well. A few sparks and streamers show luminous points on some places which may be "fireballs". I have already dwelt at some length on this fascinating phenomenon and have explained what I consider to be its true nature. It may be of interest to state that such luminous points may be produced in other ways without partaking of the nature of the fireballs. One of these ways may be described here. It is well known — at least I assume so — that by causing two or more vibrations of different pitch to pass along a conductor, nodal points and points of maximum effect may be produced and caused to shift slowly along the conductor. Such a result I have frequently obtained with two vibrations of but slightly different period, the period of one of the vibrations being adjustable. If I recollect rightly I have described a result of this kind somewhere before this.

Substituting for a conductor of copper a vacuum tube of great length, I have also produced in the latter more or less luminous strips, striae or portions which would move along the tube with a velocity dependent on the relative wave length of both the vibrations,



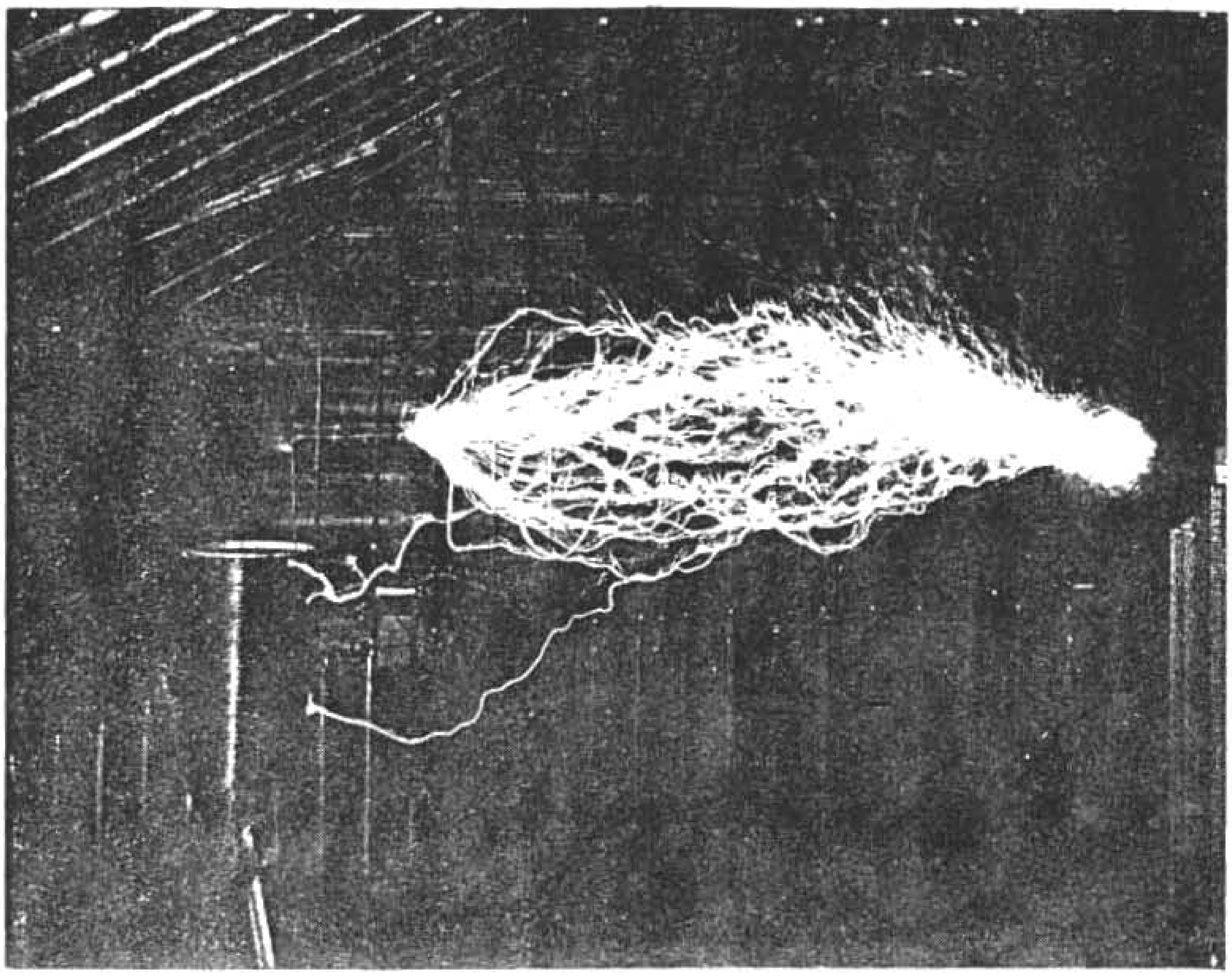
Phot. LV. "Extra coil" discharging laterally across the laboratory from the tip of a wire forming the free terminal of the coil to the floor and top wire of the secondary.

and which was at will adjustable by an adjustment of the wave length of one of the vibrations. The truth is, however, that I observed this phenomenon in vacuum tubes long before without being able to render myself an account of the nature of the same until I obtained the same effect on a wire in the manner stated. Now it is quite clear that, since a streamer is a conducting path comparable to a wire, the same phenomenon may take place on the streamer itself — being the result of two (or possibly more) vibrations of different wave length. This is all the more probable as in such an apparatus two vibrations of this kind may readily occur since the capacity, or the inductance of the circuit or both, may undergo variations as the discharge is playing, thus modifying the period to a slight extent — sufficient to cause the production of this phenomenon. In fact I have frequently observed such variations of the constants of the circuit which is oscillating, these variations being produced in various different ways. Thus it may happen that there is seen on such a long spark or streamer a point or portion of greater or smaller luminousity, or more such points, moving along the path of the discharge with a small velocity, without having anything to do with the occurrence of the fireballs, as before explained.

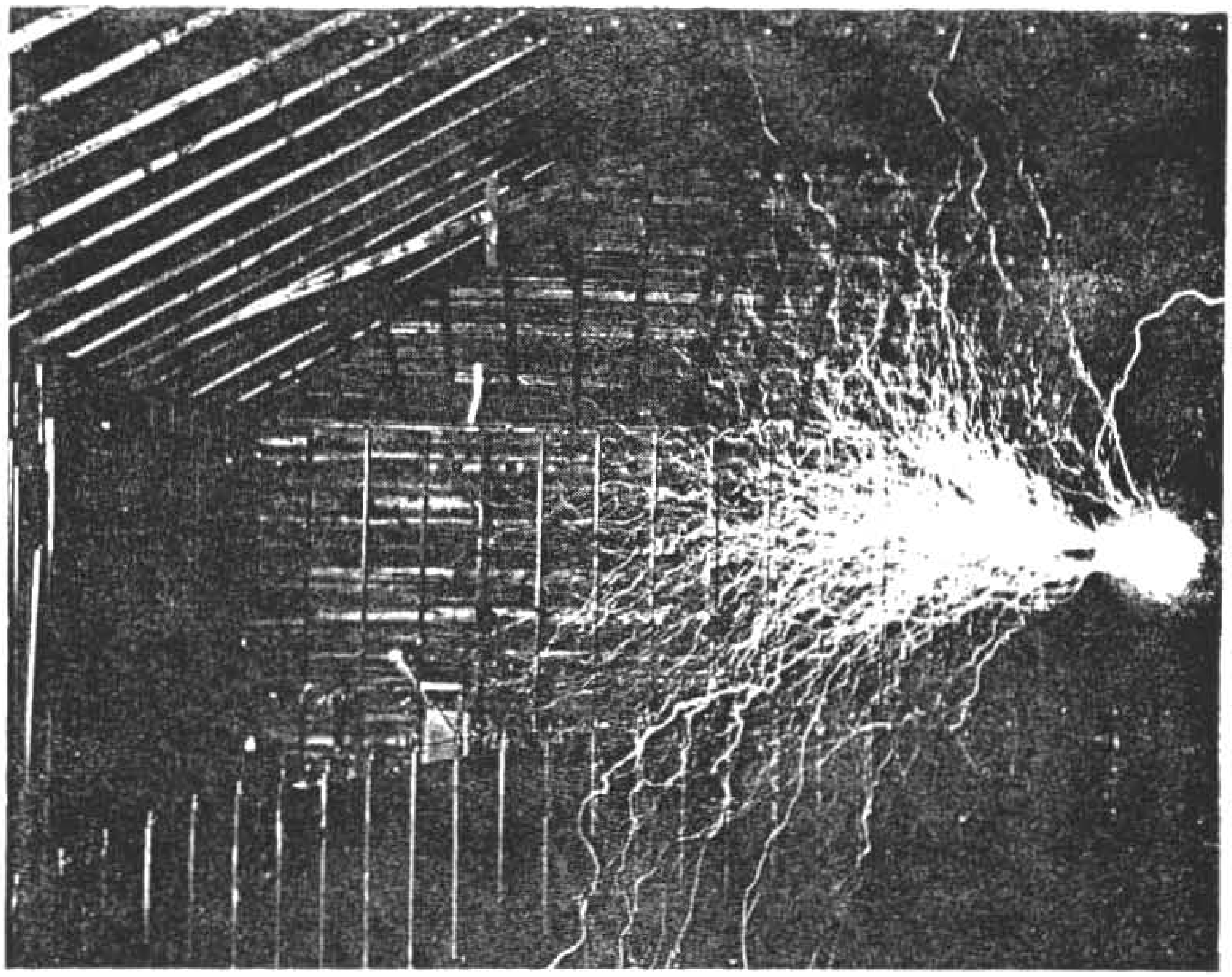
If the interruption of a discharge in some part of its course, which was noted before, would not have been actually and unmistakably observed, I would think it quite possible that this phenomenon might be due to a dark part or nodal portion formed on the streamer in the manner above set forth, this part being either stationary or slowly shifting along the path of the discharge, as the case may be. I think that I shall be able to settle this point in the following experiment which I propose to carry out. The idea is to provide a streamer which will be preferably straight and will pass continuously through the same path, thus enabling an effect propagated along the streamer to be observed just as on a wire. The streamer should be preferably also of very great length. This I am convinced I can realize as follows:

A glass tube of pieces joined together temporarily, of rather large diameter, and of a length of, say, 30 to 50 feet is to be provided. The end of a well insulated wire, forming the "free" terminal of a coil, as the extra coil here used, is to be led in one end of the glass tube, in the center of the same so that the streamer, when formed on the point of this wire, will have the tendency to pass along the tube on the inside of the same. In order, however, to keep the discharge away from the glass, suction is to be applied on the other end of the tube or else a current of air is to be forced through the tube — from the side of the discharging wire towards the other open end of the former, in any convenient way — so as to compel the streamer to pass along the axis of the glass tube. If the tube is of large diameter I do not think that it will be difficult to carry out the experiment. Now this streamer is to be produced by oscillations ot small wave length and under these conditions it will be quite easy to produce stationary or shifting, nodal or maximum points along the path of the streamer.

But, to return to the description of the present photograph, some of the paths described by the discharge are curious in the extreme. Many features dwelt upon before are again and even more clearly shown. So the "splashing", the splitting up and reuniting is plainly visible. Some streamers strike the roof and one particularly was dangerous, the plate showing that after hitting the roof it divided in three parts following the structure. *This will scarcely print.* An ignition of the roof would have been unavoidable had the switch been held on only a fraction of a second longer. But in manipulating the switch I always took care to throw off the handle instantly when, by chance, one of the discharges



Phot. LVI. Discharge of "extra coil" issuing from a ball of 30" diam. forming the "free" terminal of the coil towards a coil on a stand.



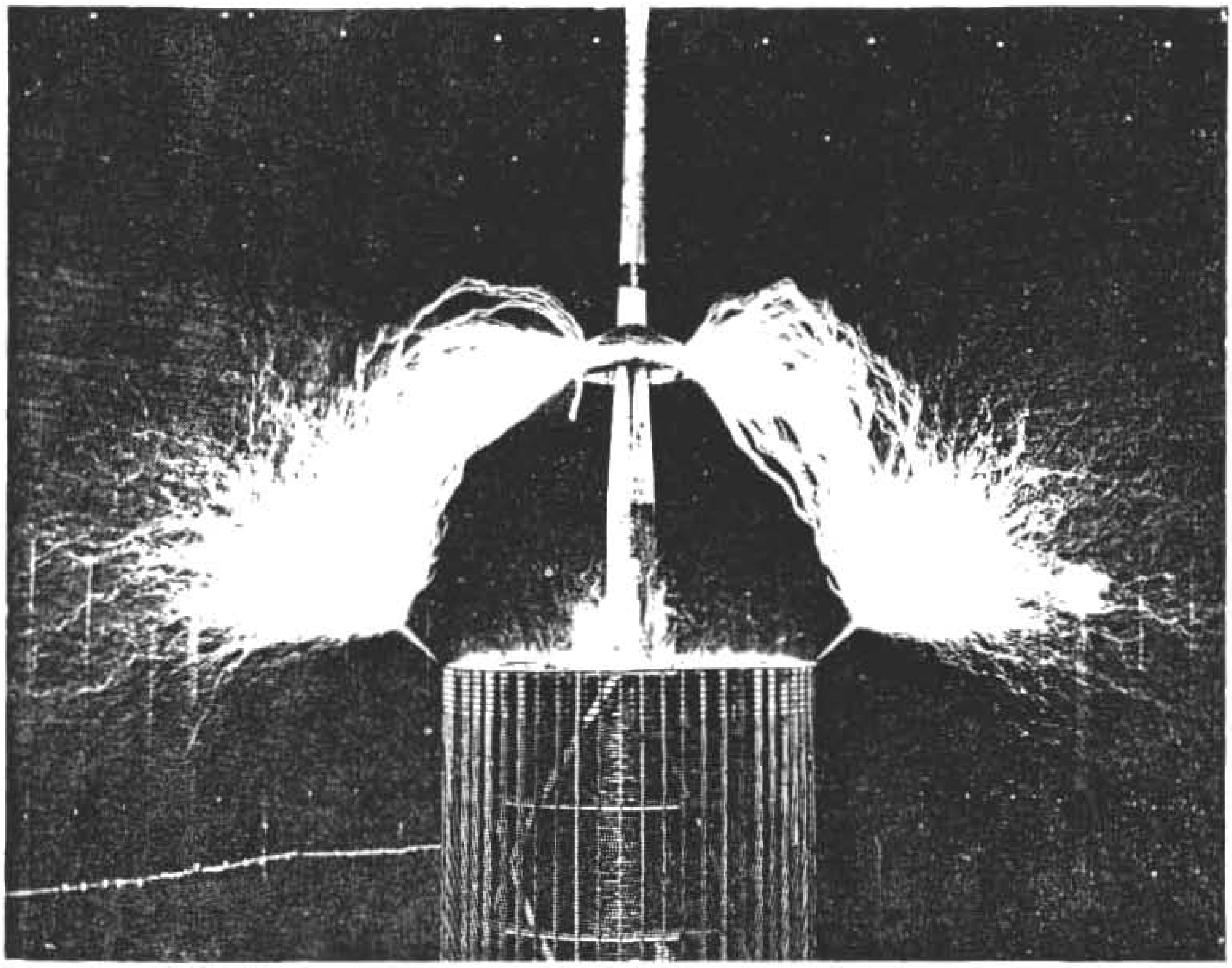
Phot. LVII. Similar as in phot. LVI but discharging across the laboratory into the air.

would dart to the roof. It is to be regretted that the building, although very large for ordinary experiments, did not allow the production of discharges still stronger than those before described, which would have been easily practicable with the present apparatus which — with more copper in the coils and particularly in the "extra coil", and possibly without any change — would have in all probability enabled me to reach twice or three times the length of the actual discharges. In the experiment a great many sparks were seen to pas to the top turn of the secondary. These discharges would, without adequate provision, infallibly injure the condensers and the Westinghouse transformer and also other apparatus connected with the circuits or at a small distance from the same, no matter how well insulated they might be. By grounding the circuits in proper ways this danger is in a large measure reduced. In the experiment just described there were again 100 closures, rather short, effected by the switch and the other particulars not dwelt upon were the same as before.

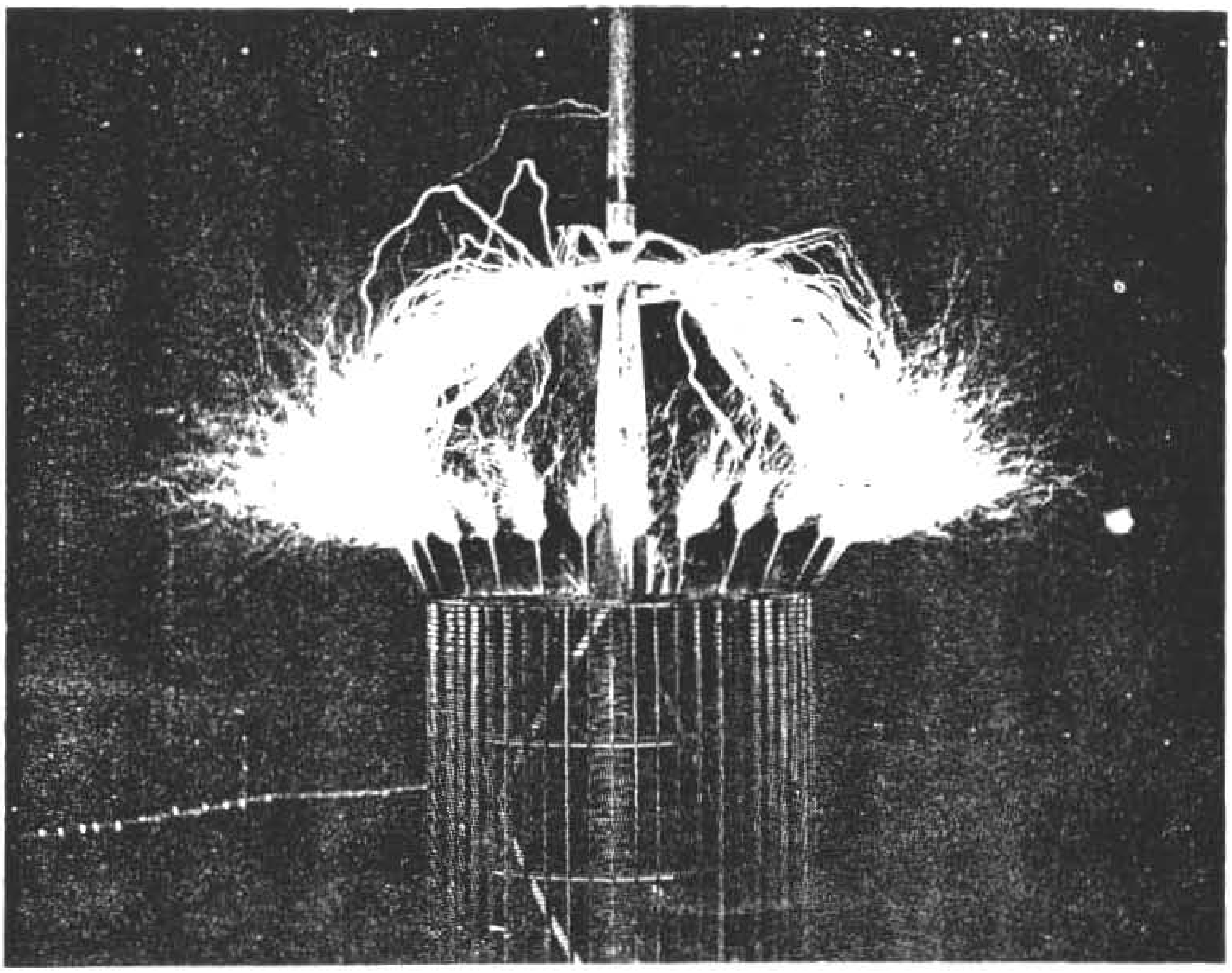
This statement repeatedly made in the description of these plates should be specified. The truth is, each experiment required a special adjustment as the size and form of the terminals and the character of the discharge affected, to some extent, the constants of the oscillating system or systems. But the departures from the conditions designated as normal were very slight, the inductance of the primary or exciting circuit being varied only by inserting a very few turns of the regulating coil.

LVI. In this photograph the discharge of the extra coil, issuing from a ball of 30" diameter forming the "free" terminal, passes across the laboratory to a wire turned toward and extending from the top of a coil on a stand. The discharge is made of smaller length for the purpose of heightening its brilliance. The shortest distance in a straight line from the ball to the wire is eleven feet. As the light of the sparks would produce a marring of the images, the photograph is taken through a diaphragm with a very small oponing. The individual discharges corresponding to the closures of the circuit by the break wheel are very clearly shown. It is interesting to observe the curved paths of the sparks which are much longer than the shortest route open to them. Some of the sparks avoid the wire preferring to pass through fully twice the distance through the air. An interesting feature is afforded by one of the longest streamers which in a portion nearer to the wire, extending from the coil on the stand, changes from a *streamer* into a *spark*. It is also curious to observe its path passing far beyond the wire point and returning to the same. In this instance there were 50 throws of the switch made and the vibration was slightly slower than the normal on account of the large ball at the free terminal.

LVII. This plate shows the extra coil, with a ball of 30" diam. as "free" terminal, discharging laterally across the laboratory into the air. The discharges are much stronger when breaking out from the ball, requiring a much higher e.m.f. Capacity also adds to their volume and fierceness. Many streamers again show luminous points and attain great length, one in particular, which traverses the entire laboratory striking the wall. The end is probably too fine to print clearly. Many discharges again are carried to the roof by the draught they create. Once more 100 throws of the switch were made. The conditions were otherwise the same.



Phot. LVIII. Discharge from "extra coil" issuing from two diametrically opposite wires, pointing upwards and fastened to the brass ring on the top of the coil.



Phot. LIX. Discharge of "extra coil" issuing from many wires fastened to the brass ring as on phot. LVIII.

Colorado Springs

Jan. 7, 1900

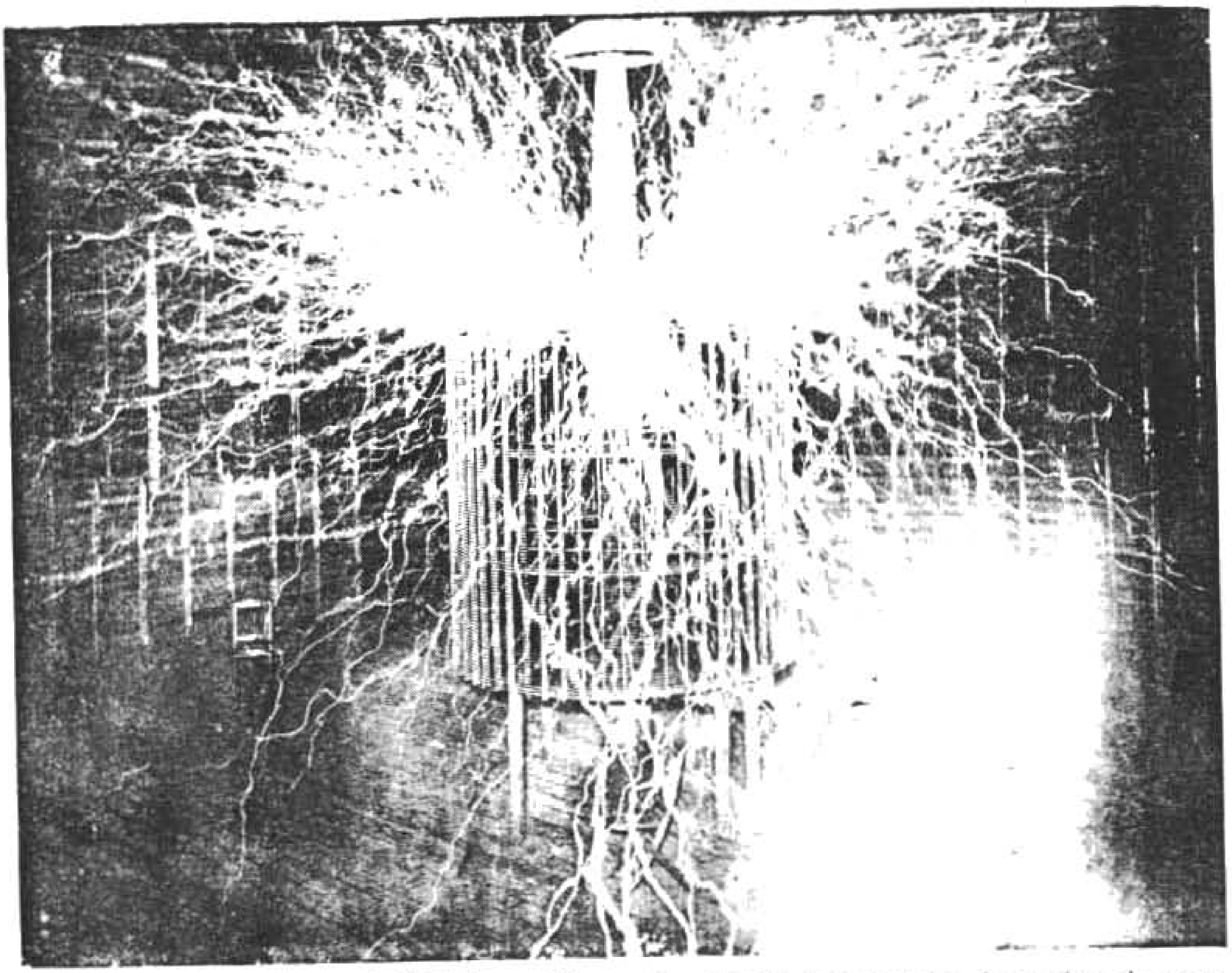
Photographs taken with Mr. Alley from Dec. 17 to Dec. 31, 1899 and *particulars* about the same continued:

LVIII. This photograph shows the extra coil in central view with the discharge issuing from two diametrically opposite wires, pointing upwards, which are fastened to the brass ring or last turn on the top. The sparks, passing abundantly to the hood above the coil, produce a most beautiful symmetrical figure, which is rendered still more so by the fine texture and sharpness of the discharge paths. On the top of the coil from the brass ring delicate streamers rise producing the effect of a flame. The two wires from the ends of which the sparks and streamers sally forth *glow all along*. This is remarkable and indicates the great quantity of electrical movement. The glow of the top turn of the secondary and also that of the wire leading to the extra coil is strong, that of the latter wire being much stronger. Some exceptionally brilliant sparks occur occasionally. This happens when the discharge breaks out on one wire or point much earlier. In this case the spark continues along this path and practically all the energy supplied goes this way. In the experiment, as in most cases before, 100 throws of the switch were made, other particulars remaining unchanged.

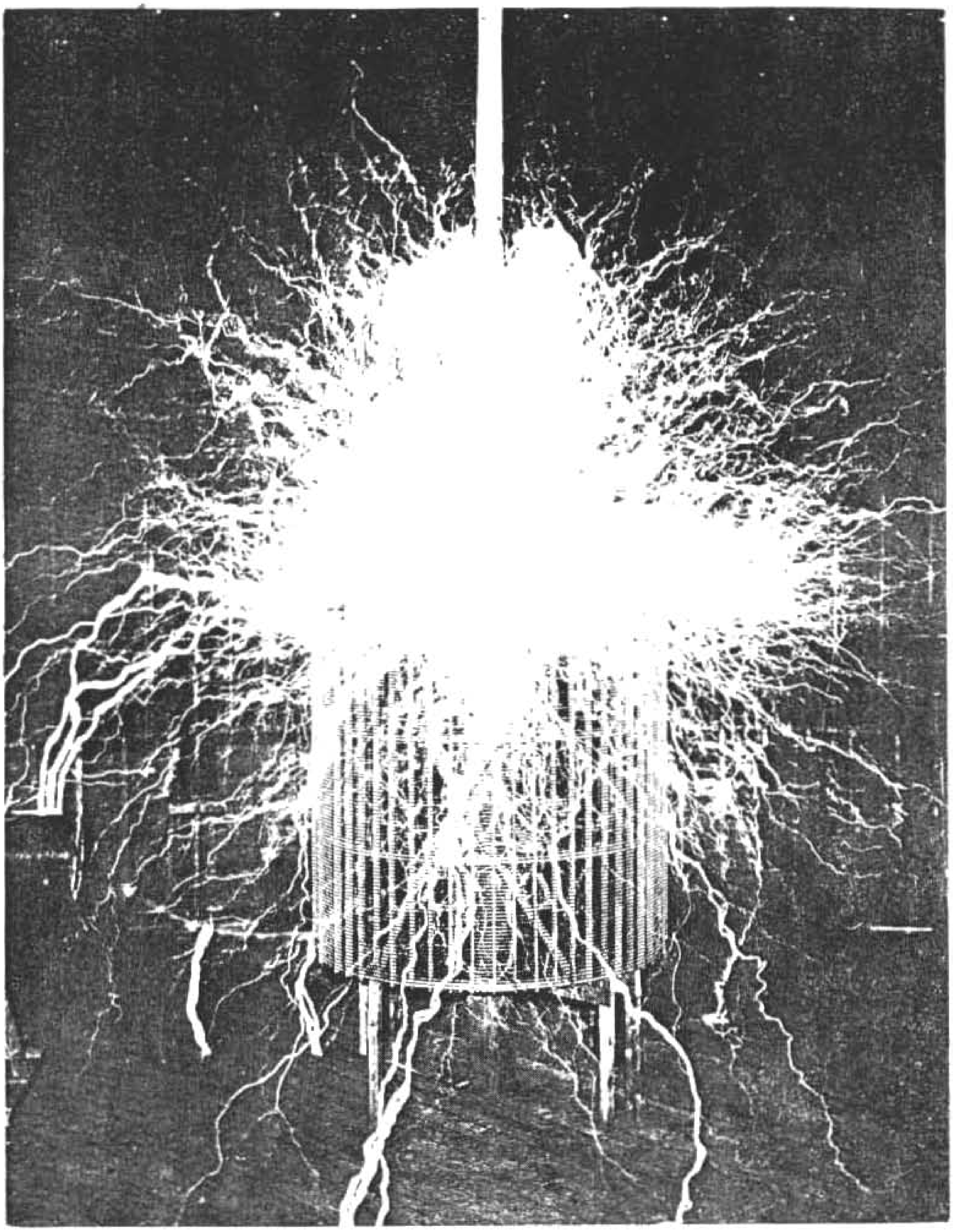
LIX. In this plate the extra coil is again shown in central view, only the discharge is made to issue from many wires instead of only from two as before. The wires are fastened to the brass ring and are pointed upward as in the preceding case. This photograph is also symmetrical and extremely beautiful. Some stronger sparks and streamers occurring occasionally present many features of interest. A number of sparks starting from the back avoid the hood, though passing near the same, circle around and finally strike the hood on the front side. One streamer, extremely long, starts upward following the pole for some distance then turns, passing for a good distance horizontally, and finally darts upward through the opening in the roof, evidently carried by a sudden gust of the draught. Several sparks pass closely to the hood upward and return to the same after traversing a considerable distance. All the wires emitting the streamers glow. Again 100 throws of the switch were made and the vibration, as well as other particulars, remained nearly normal.

LX. This is a very interesting plate, the discharge taking place from a ball of 8" diam. and two diametrically opposite wires fastened to the same. The extra coil is again viewed centrally. Very strong sparks pass to the floor, some twisting and darting about curiously and exhibiting several phenomena described already. Sparks and streamers also pass to hood, roof and sides of the building. Some of the streamers attain great length being thirty feet, at least, in a straight line, while some sparks measure twenty feet or more. These latter are very brilliant and fierce. The upper streamers indicate the existence of a strong current of air created by the heat developed by the discharge. Again 100 throws of the switch were made, other particulars remaining the same.

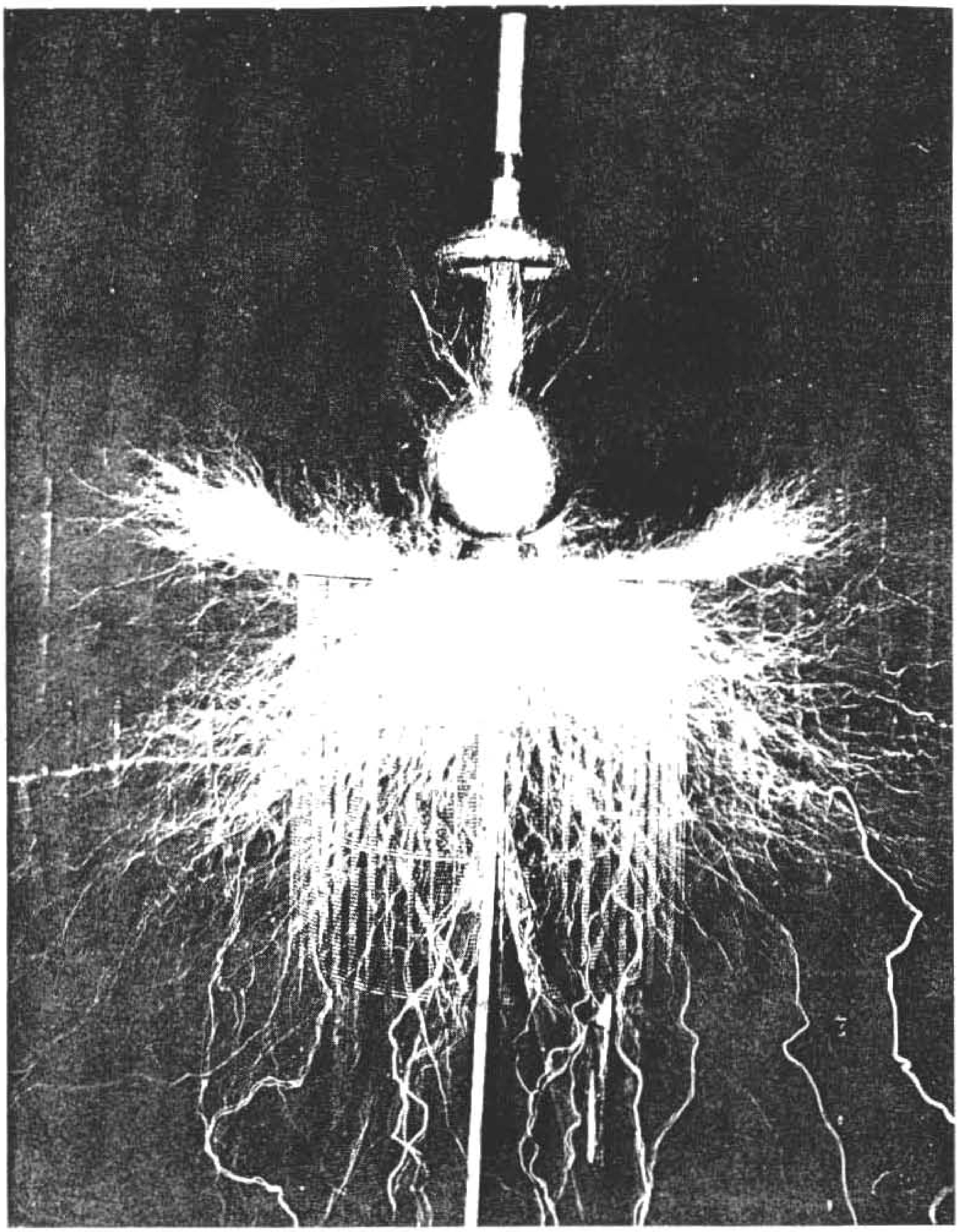
LXI. This is another most beautiful photograph showing streamers and sparks issuing from a disk facing the camera. The extra coil is viewed centrally, as before, the disk forming the free terminal being on a point of the vertical axis of the coil. It seems that in some quick moving streamers the individual discharges are recorded, at least the texture appears far too fine for the break wheel period. Assume, for example, 4000 breaks per



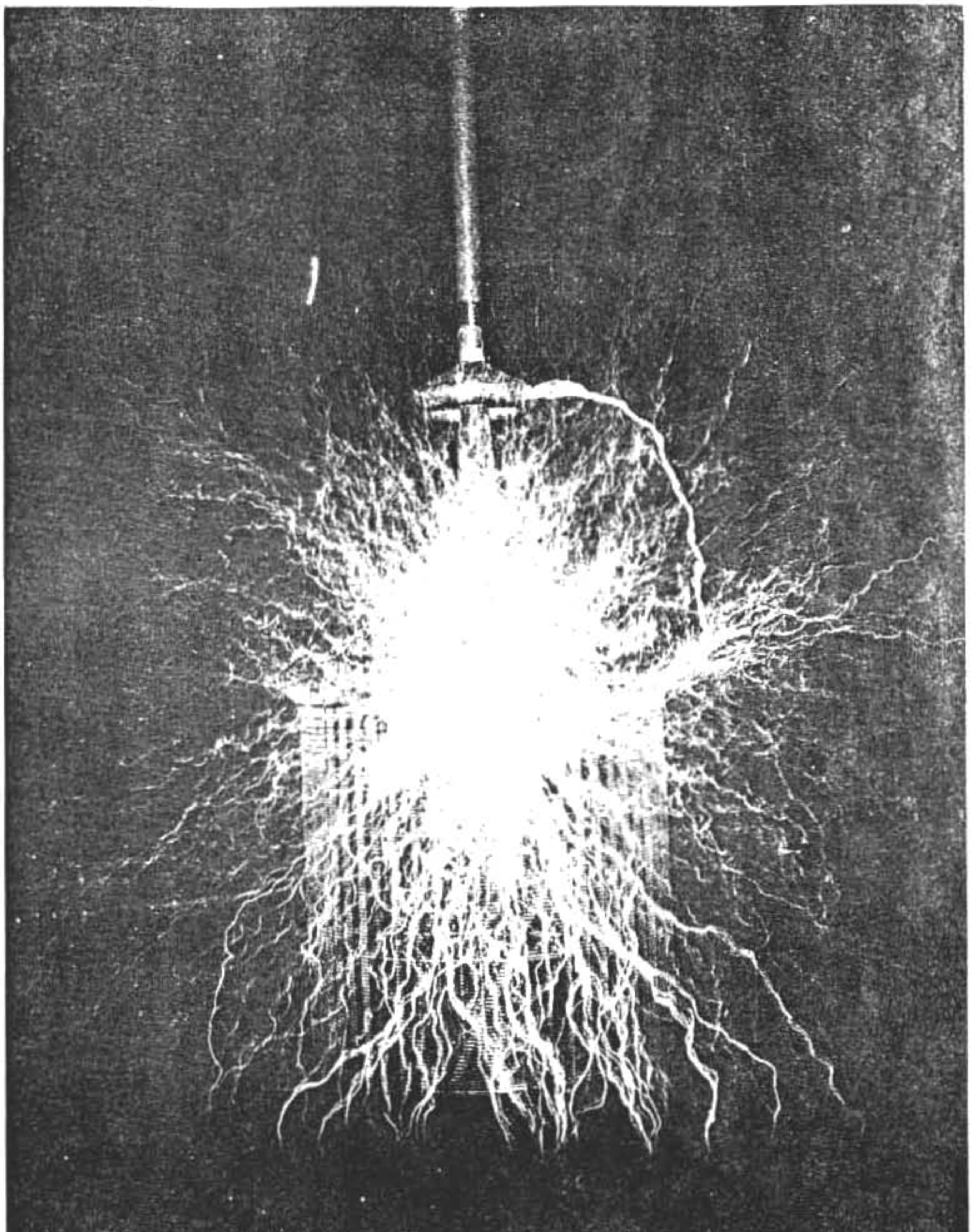
Phot. LX. Discharge from a ball 8'' diam. with two diametrically opposite wires fastened to the same.



Phot. LXI. Streamers and sparks issuing from a disk facing the camera.



[illegible] LXII. Discharges [illegible] from the base of a cone upon which a ball of 30 [illegible] diam. is resting



Phot. LXIII. Discharge from a ball 30″ diam. supported on a vertical coil.

second and let the vibration be, say, 60,000 per second — then there would be 30 individual discharges in each break wheel period, understanding by this the time interval from one break to the next, or from one closure to the next. Since the break wheel effect is always seen, even when the streamer moves slowly, it would seem that the finer threads indicate the individual discharges. At any rate, with a stronger draught the latter can be evidently easily recorded and this might be a simple way of exactly determining the vibration of the system, certainly simpler than analysis by a revolving mirror.

This experiment I expect to perform on my return for it is indispensable to determine the vibration quite exactly. Up to the present this necessity was not imperative, the method used being satisfactory so long as the chief purpose was to perfect the apparatus and make general observations. But now quantitative estimates have become important. To return to the description, the strong sparks to the hood are particularly curious. The strong current of air is evident from their behaviour and also from the appearance of the upper streamers. Some very strong sparks pass to the coil in series with the extra coil. One of the streamers striking the floor ignites the wood. Many streamers are carried through the opening in the roof. One, exceptionally long, passes to the photographer in the corner of the building. The shock is but slight as might be expected. ~~A~~ *spark* might be fatal, but there was no possibility of a spark taking that course without being stopped by conducting objects nearer to the origin. Some of the upper streamers are chopped up curiously indicating the presence of small whirls or eddies in the air current passing through the roof opening. The switch was here also closed 100 times; the closures were very short and the other particulars remained as before.

LXII. This is one of the most beautiful plates taken. It shows a discharge issuing from the base of a cone upon which a ball of 30" diameter is resting. Streamers, though a few only, issue also from the ball giving evidence of the immense electrical pressure and quantity of electric movement. It was indispensable to employ the metallic conical vessel for the purpose of preventing the discharge from following the wooden support, upon which the ball of 30" was supported, to the ground. This would unavoidable occur even if the support were of the most excellent material as regards insulation, as of glass for example, and no matter how high the support might be.

In fact, I have found from long experience with these discharges of extreme electromotive force, that it is almost impossible to insulate a terminal without some such provision as used in the present instance. The fundamental idea is to provide an arrangement such that the place of support, or that part of the terminal which rests upon the support, is guarded by the conductor projecting beyond. In other words the terminal must be resting on the support on points where there is *no electrical* pressure or, at any rate, a very small pressure. This amounts to screening the support statically. Another way to prevent the current from following the support is to place a coil, through which the current passes, beneath the support passing axially through the coil. The hood, referred to repeatedly in these descriptions, is used for the same purpose as without the same the current would pass along the pole to the ground. But the hood might be dispensed with by using an extra coil of much smaller diameter, axial with the wooden pole supporting the iron structure, but it would be necessary for insuring safety to let the coil finish very close to the bottom of the iron structure where it rests upon the insulating support. This has been one of the great difficulties encountered in the course of this work and it has required much time and trouble to overcome it successfully. For the same purposes also the large hood, above the cords keeping the iron pole in position, is employed. The rims of both these hoods are curved so as to enable a greater pressure to be reached by preventing the streamers to break out into the air easily and at a much smaller pressure. In a new apparatus, now under consideration, these improvements will be carried much further and I am confident to obtain results far beyond anything arrived at so far.

In the present experiment it is rather astonishing to see some streamers breaking out from the surface of the ball of such a large radius of curvature, when they can pass out so easily from the edge or base of the cone underneath. This shows the existence of violent surgings and a great quantity of electricity set in motion in the system. The photograph shows some luminous spots on a very powerful streamer passing to the floor. Many sparks are very curious on account of the curved paths they follow. The streamers here are also mostly of fine texture, this being due to the facility with which they break forth from the edge of the inverted pass and to their abundance. It may be seen from the plate that one of the supports of the extra coil caught fire. The particulars in this experiment were as in most cases before, 100 throws of the switch being made.

LXIII. This plate again illustrates a most beautiful discharge taking place from a ball of 30" diameter supported on a vertical coil. Owing to the abundance of the streamers the ball can not be seen. The streamers are of a peculiar character, probably due to the manner in which they were produced, which is different from that practiced in the instances before described. It so happened that when the switch was thrown in the discharge from the ball always darted to the floor. Now, in order to make it pass upward also and so to produce a symmetrical figure, I held the switch on longer expecting that the heated air rising upward would carry the discharge towards the roof. Indeed this happened, the discharge always starting towards the floor and then gradually rising until it was vertical and passing out through the opening in the roof. The last and permanent position was attained in 3—4 seconds of time, this showing the great amount of energy spent in heating the air and rapid heating and rising of the latter. The air current exercises such a predominating influence that some streamers pass vertically upwards very close to the iron pole, without apparently being affected by the presence of the pole.

A peculiar feature of the present photograph is that the upper streamers are not sharp although the focusing was carefully done. This is evidently due to their fluttering motion caused by the sudden and changing gusts of the draught. This again forcibly illustrates the great sensitiveness of such streamers to air currents and I am once more impressed with the possibility of turning this property to some good use. The symmetry of the photograph is somewhat destroyed by a spark, which breaking the insulation of the top turn (3/8" rubber), passes to the hood above the coil. All the particulars in this case remained nearly normal. There were again 100 throws of switch made.

Aleksandar Marinčić

COMMENTARIES

In Colorado Springs' Memorial Park, near site of Tesla's experimental station, an historic marker notes the association

1 *June*

Tesla mentioned a similar application of a magnet for extinction of the arc in rarefied gas in his lecture to the IEE in London 1892[5]. The initial idea for this type of detector may date from the time when he was intensively studying phenomena associated with currents in vacuum.

3 *June*

During the year 1899 Tesla filed applications for four patents[8–11] which made use of the principle of "accumulating energy of feeble impulses". It may be seen from these patents that the function of the capacitor was to store energy from the commutated (in fact rectified) HF current. The condenser is connected to the receiver (a relay) which periodically makes contact[8,10] when the condenser charges up enough. Both these patents were filed 24th June 1899[8,10]. The other two[9,11] were filed 1st August 1899. They also refer to a method of accumulating energy but the way the incoming signal controls the charging of the condenser is different: here it causes variations in the resistance of a "sensitive device" which controls the current charging the condenser from a battery. The condenser discharges periodically through the receiver as in the previous case.

Tesla developed the magnet method while he was in Colorado Springs.

5 *June*

Tesla does not state the origin of the formula he uses to calculate M, the power induced in the secondary, receiving coil, by the primary fed with a power of 4 kW (or 4×10^{10} erg/sec, not ergs). Although he himself expresses doubts about the calculation, the conclusion he draws is correct, i.e. that these mode of transmission is greatly inferior to that which he calls the method of "disturbed charge of ground and air", in fact that of electromagnetic radiation.

6 *June*

Working with a darkened Crooke's tube, on the 8th of November 1895 Röntgen noted the luminescence of barium platino-cyanide crystals and discovered that it was due to some unknown radiation which he termed X-rays. Towards the end of that year he held a lecture on his discovery, and in an amazingly short time the whole world knew about his work[66].

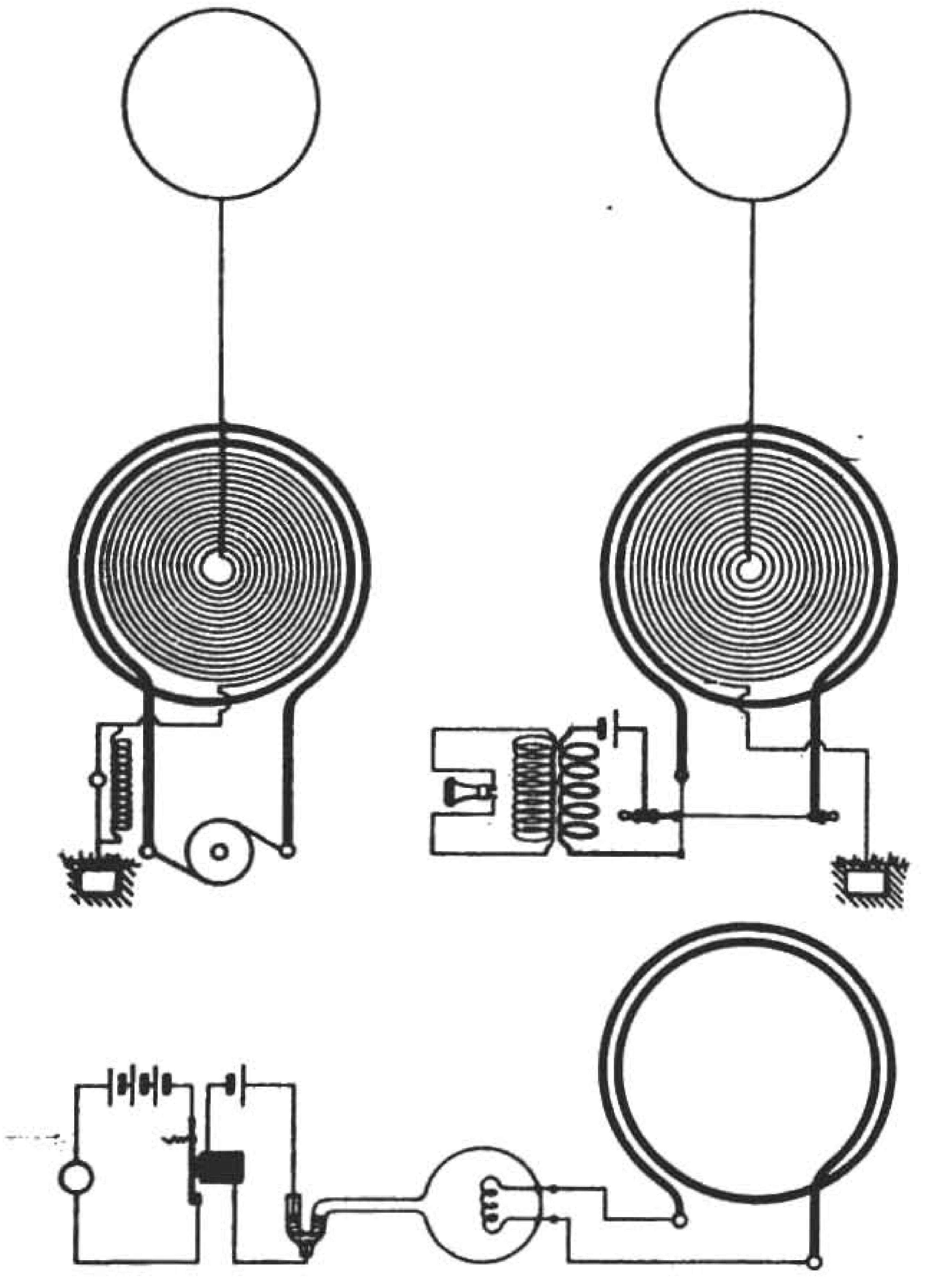
Tesla spent some time in intensive research on X-rays, publishing his results in ten articles in the period 11th March 1896 to 11th August 1897(7). On the 6th of April 1897 he also gave a lecture on his X-ray studies(17) and presented designs of a number of devices for generating powerful rays. During this lecture he reported interesting data from his earlier experiments with Crooke's tubes in 1894. He had then observed that some tubes which produced only feeble visible light had more effect on photographic plates than tubes which were brighter to the eye. The goal of his research was to obtain true phosphorescence ("cold light"), so that he postponed further investigation of this phenomenon, and of the cause of various spots and hazing on photographic plates which had been kept in the laboratory for a time before use. When he finaly did get around to it a fire broke out in the laboratory, destroying practically everything (13th March 1895). It was several months before he could resume his work, and in the meantime Röntgen made his discovery. When Tesla heard about it, it was immediately plain what had been happening in his laboratory. He repeated Röntgen's experiments, which were rather cryptically described, and realized that he had been mistaken in not following up certain chance observations during his work with Crooke's tubes.

During 1896 and 1897 Tesla carried out many experiments with X-rays, also speculating about their nature. He thought "that the effects on the sensitive plate are due to projected particles, or else to vibration far beyond any frequency which we are able to obtain by means of condenser discharges" (Lit. (1), p. A-30). He immediately realized the importance of high voltages for producing powerful rays and suggested using his single-terminal tubes connected to the secondary of the disruptive discharge coil. It is interesting to note that Röntgen too, in a lecture to the Physical Medical Society of Würzburg the same month as Tesla published his first article, also pointed out the great advantage of using Tesla's high-frequency oscillator in generating X-rays.(66)

Tesla measured the reflection and transmission of X-rays for several metals, lead glass, mica and ebonite. It is not clear, however, whether what he measured was true reflected radiation or secondary radiation. He also tried to detect refraction but did not succeed, for reasons which are today obvious. In papers and in a lecture before the New York Academy of Science he described a number of tubes for producing powerful X-rays, most of them resembling Lenard tubes (which he often mentions) but without the anode terminal.

7 *June*

Descriptions of the high-frequency transformer are to be found in Tesla's publications and patents from 1891 onwards(15,4), but he did not patent it until 1897(26). The invention protected by this patent is "A transformer for developing or converting currents of high potential, comprising a primary and secondary coil, one terminal of the secondary being electrically connected with the primary, and with earth when the transformer is in use, as set forth". It in particular protects the spiral form of the secondary, and a conical form is also mentioned. For ordinary uses a cylindrical secondary divided into two parts is proposed. A new feature is the specification that the length of the secondary should be "approximately one quarter of the wavelength of the electrical disturbance in the secondary circuit, based on the velocity of propagation of the electrical disturbance through the coil itself", or, in general, "so that at one terminal the potential would be zero and at the other maximum".



WITNESSES: INVENTOR.

BY

ATTORNEY.

9—12 *June*

In his efforts to construct a sensitive detector for small signals Tesla worked out several designs making use of the thermal effect of high-frequency current. Since the energies involved are very small (according to Tesla of the order of 1 erg), receivers based on this principle would be extremely delicate.

In the archives of the Nikola Tesla Museum, Belgrade, a slide has been found which evidences that Tesla was probably preparing to file a patent on a receiver similar to that which he described in the diary the 9th of June (see drawing on p. 399). The entry for 11th June is stamped on the back "U.S. Patent Office, Nov. 15, 1902."

The basic principle of these detectors is of an earlier date. According to Fleming[33], Gregory carried out measurements of radiation intensity by the extension of a thin wire in 1889, and Rubens and Ritter in 1890 using a bolometer.

13 *and* 14 *June*

From the very start of his work on wireless transmission of signals in 1892—1893 Tesla advocated the use of continuous HF current, while other experimenters were working with damped impulses. The advantage of continuous currents is particularly great in the transmission of continuous signals, such as speech. The entries for the 13th and 14th of June describe two modifications of the HF oscillator which could be used for amplitude modulation. These two circuits were probably in fact the first modulators in the history of radio. It is not known whether Tesla carried out any experiments with this apparatus, but similar ideas were implemented later[19].

Tesla's notes illustrate how carefully he studied the design, from the power supply to theoretical aspects such as the ratio of the maximum modulation frequency to the carrier frequency.

The transmitter using "controlled arc" modulation of the oscillator power described in the entry of June 14th produces amplitude modulated wave by varying the carrier power about a mean value. The modulating signal can be of low power, so that the device as a whole can also be considered a frequency-shifting amplifier.

15 *June*

This trial run of the new oscillator was Tesla's first step towards the implementation of his high-power generator. The secondary of the HF transformer was made conical in order to reduce the voltage between turns at the top of the coil. This feature is described as one of the alternatives in his "Electrical Transformer" patent[26]. Tesla was the first to suggest using braided insulated wires instead of solid conductors in HF circuits in order to reduce eddy currents (see e.g. ref. 46, p. 60).

16 *June*

In these experiments Tesla investigated the influence of grounding* on the HF oscillator. The main point of interest for him was the propagation of electrical waves

* At this time there was relatively little experience with grounding. He explains in this entry that grounding was made in "the usual way as here practised", probably referring to lightning conductor grounding. Grounding for single-wire telegraphy dates from 1838, when Stinheil demonstrated that the Earth could be used as the return conductor. In 1893 Tesla described his system for energy transmission

through the Earth. He had already put forward the hypothesis that the Earth could be used as one of the conductors in transmission of energy from a transmitting to a receiving aerial in 1893(6). He further developed this hypothesis in his patent application "Apparatus for transmission of electrical energy" filed in 1897(13).

18 *June*

The secondary circuit was modified by the addition of another coil, altering its response to the primary and the spectrum of the oscillations. Tesla had already found in experiments in New York that this "extra coil" had a good effect. This coil was not inductively coupled to the transformer (some coupling probably existed, though weak).

19 *June*

Continuing his study of the receiver components referred to between 9th and 11th June, Tesla describes a sensitive detector using the attractive force between the plates of a charged condenser. Descriptions of allied devices are to be found in several of Tesla's patents. In patents(8) and (9) this effect is used to periodically make the receiver circuit when main condenser charges up sufficiently (there is no preexcitation nor quenching, since the circuit quenches itself when all the stored energy gets discharged). A fuller description, where it is noted that the performance of the device is improved under reduced air pressure, may be found in patents(70).

20 *June*

Tesla did not make a strict theoretical analysis of the mode of operation of his oscillator, but determined all the main parameters by tests on a simplified representation of the oscillator circuit. For example, he estimated the power supply drain from the energy in the primary circuit capacity multiplied by the rate of discharge. This involves the assumption that the condenser charges up by the same amount before each discharge (which cannot be the case when it is charged from an AC supply) and that all the energy gets dissipated before the next charging.

The "vibration", i.e. the resonant frequency of the primary circuit is calculated from the measured inductivity of the primary with two turns (see June 17th) and its capacity. Since he was now using one turn, the inductance is divided by 4. The capacitance was somewhat greater than that measured on June 18th with the old jars. Using these L and C values he calculates the resonance period of the primary using Thomson's formula for a lossless circuit.

He then finds the wavelength of the primary oscillations, and hence works out the number of turns the secondary must have so that its length is one quarter of a wavelength (see the commentary to 7th June). It is not surprising that he went astray in trying to set up a representation of the secondary circuit as an oscillatory system since the distributed

without wires(6) where the alternating current source is connected "with one of its terminals to earth (conveniently to the water mains) and with the other to a body of large surface P". Popov's receiver of 1895 also used grounding via a water pipe(32). Around 1895 Marconi did some experiments with a Hertz apparatus grounding one terminal of the inductor and leaving the other connected to an elevated conductor with a terminal capacity. Exhaustive studies of the influence of the form of grounding and the nature of the ground were made around 1905 and later(30).

capacitance was not determined. Tesla's own doubts about this way of determining the secondary in terms of length of wire are best revealed when he refers to checking its resonant frequency treating it as an oscillatory circuit.

21 *June*

Returning once more to the problem of the conversion of mains power into HF power Tesla calculates the energy in each charging cycle of the condenser (see comments for June 20th). Taking it that all the energy in the charge condenser will at some instant be found in the condenser of the secondary circuit, he in fact works out the peak voltage on the secondary condenser. The energy equation for lossless coupled circuits has the general form

$$\frac{1}{2} C_p U_p^2 = \frac{1}{2} C_s U_s^2$$

where p refers to the primary, s to the secondary circuit, U is peak voltage. It should be noted that Oberbeck's theory[29] yields the same ratio between the voltage on the primary condenser just before discharge begins and the peak voltage on the secondaıy condenser.

22 *June*

The circuit with two condensers, one being charged from the power supply and the second via a spark from the first represents a modification of Tesla's classic oscillator*. Theory shows that protraction of the oscillation in the primary circuit lowers the efficiency of the oscillator because energy pulses back and forth between the primary and secondary. However, in this circuit protraction of the spark does not have the same effect because while it lasts the primary capacitance is $C+C_1$, but when it stops the capacitance is only C_1. Why the sparks in the secondary were stronger with $C=aC_1$, a a whole number, is hard to say without a more exhaustive analysis.

The note at the end of the entry indicates his satisfaction with the results and that he felt it necessary to continue research in the same direction.

23 *June*

The two formulae are in fact identical if the thickness of the wire is neglected, because then

$$\mathfrak{L}^2 = (2\pi r N)^2 = 4\pi S N^2$$

24 *June*

Rarefied gases had long interested Tesla, and his work on their conducting properties, especially at high frequencies, is well known, e.g. the patents on an electıic lighting system and an incandescent lamp[37]. He presented detailed analyses of the same problems in his famous lectures[4,5,6]. Rarefied gas as a conductor is also referred to in his patent application "System of transmission of electrical energy"[13].

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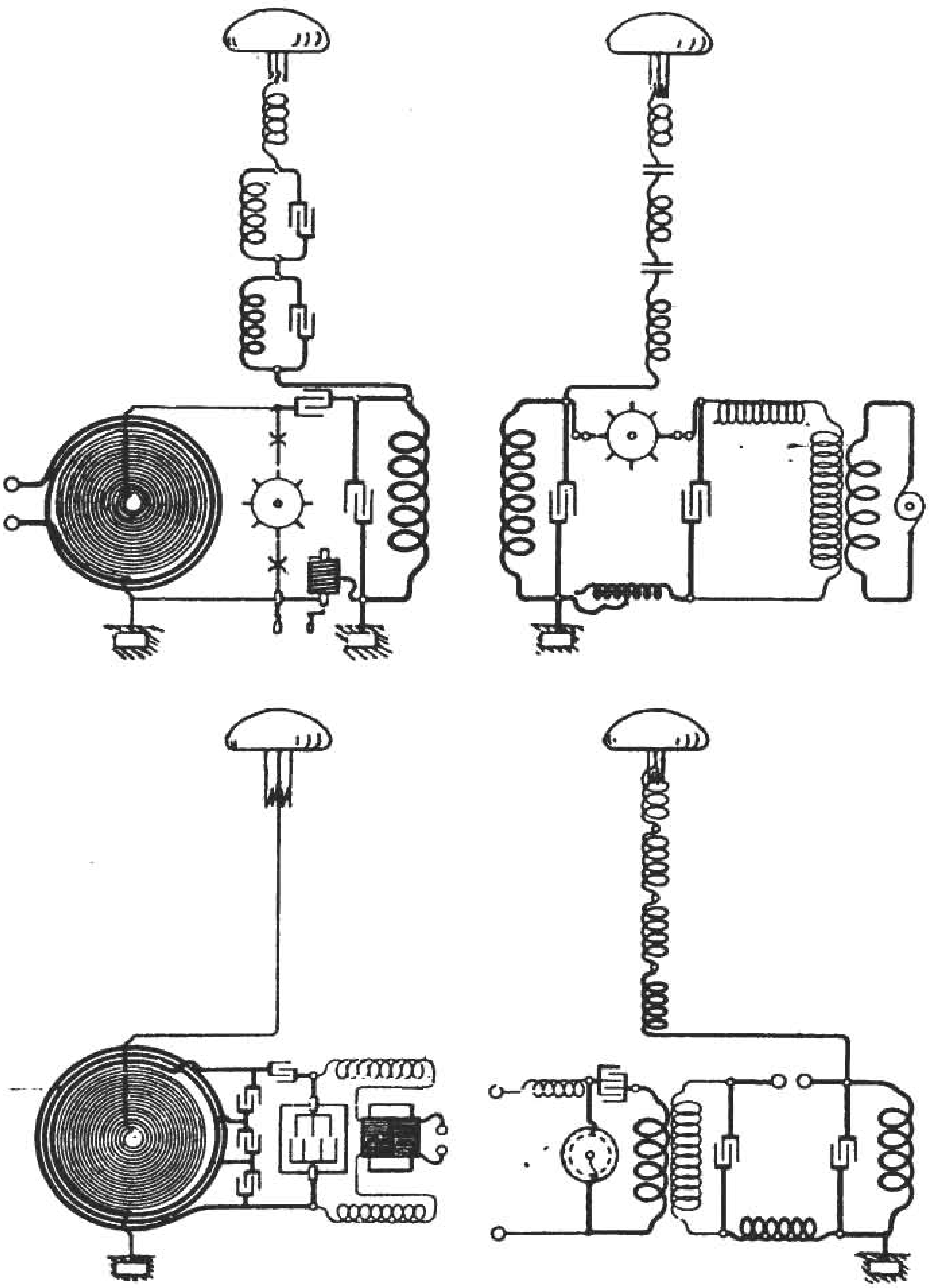
* Drawings reproduced on p. 403 are taken from Tesla's original slide, now in the Nikola Tesla Museum, Belgrade, show four modifications of the transmitter.



WITNESSES

INVENTOR.

BY

ATTORNEY.

25 *June*

The device shown in the drawing was intended to amplify the vibrations, in the following way: some of the power driving cylinder A is converted by friction of brush b against A into vibrations of b. Since the friction is a function of the current in the electromagnet, the vibrations of b have a time variation similar to the time variations of the current. If the circuit of the electromagnet includes a microphone and a battery, then the device should amplify the speech signal, brush b vibrating in synchronization with the speech pressure but with much more energy. This amplified signal could be used in a modulator (see June 13th and 14th). The drawing shown on p. 405 (from Tesla's slide in Nikola Tesla Museum, Belgrade) illustrates how Tesla thought of implementing some of these ideas*.

26 *June*

The principle of this device using high voltages to separate gases would be that the molecules (in fact ions) of the different gases would behave differently because of their different mass: charge ratios. It is not known whether Tesla tried to verify this idea experimentally. In a later article[28] on electrical oscillators he mentions among the possible applications "formation of chemical compounds through fusion and combination; synthesis of gases; manufacture of ozone . . ." but does not mention separation of gases, so that it may be he never went any further than the initial idea.

27 *June*

The transmitter (Figs. 1 and 2) and receiver (Fig. 3) having several tuned circuits, the transmitter generating several signals at different frequencies and the receiver responding only when all these signals act at the same time, were the subject of two patent applications filed 16 July 1900 (subsequently granted)[38].

This method allows much more selective reception than a single-frequency channel, and is much less sensitive to interference, and the signal can only be decoded by a special receiver. In his patent applications Tesla likens it to a lock which can only be opened when one knows the combination.

The entry of June 27th was subsequently brought in evidence in a dispute before the U.S. Patent Office about priority to the idea of a multi-frequency system[68]. The back of the page bears the stamp "U.S. Patent Office, Nov. 1902".

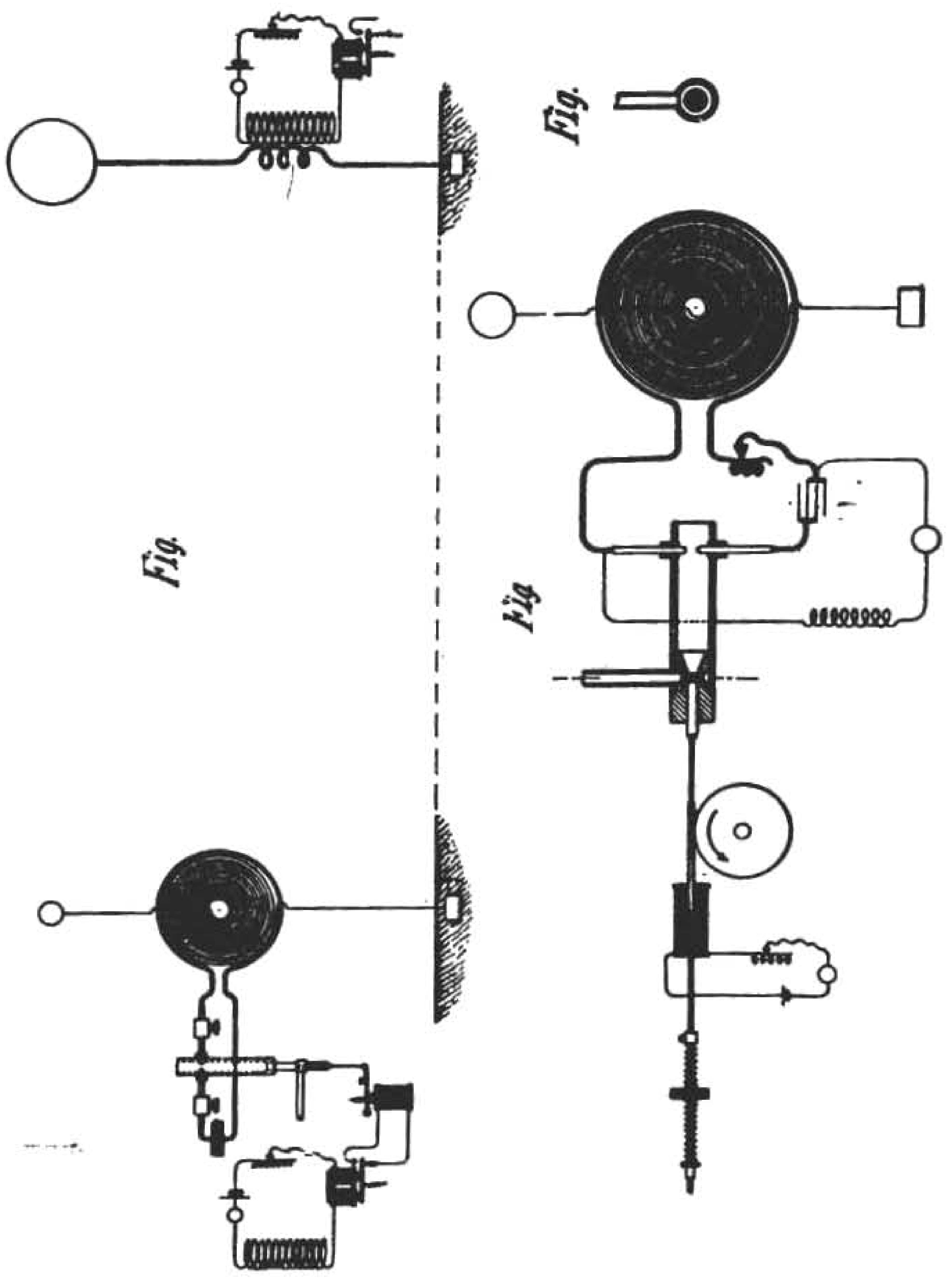
28 *June*

Tesla considered that the self-capacity of the secondary winding was proportional to the number of turns and inversely proportional to the spacing between turns, so that the ratio of the distributed capacities of the new and the old coil is $N_1\, d/N\, d_1$ (N — number of turns, d — spacing between turns).

The ratio of the inductance of the secondaries with different numbers of turns he finds from the relation

$$\left(\frac{N_1}{N}\right)^2 \frac{l}{l_1} = \left(\frac{N_1}{N}\right)^2 \frac{Nd}{N_1 d_1} = \frac{N_1\, d}{N d_1}$$

* It has not so far been established whether Tesla patented or tried to patent this modulator. It appears that the slide is a copy of a drawing intended for a patent application.



Witnesses: *Nikola Tesla, Inventor*

by *Attys*

derived from the expression for an infinitely long coil, and yielding the same ratio as in the case of capacitance.

The numerical value for the capacitance of the old coil appears here for the first time, without explanation.

The receiver experiments were probably done in preparation for a patent application. Leonard E. Curtis appears a number of times as a witness to Tesla's patents (see for example refs. 8, 10), or as one of the attorneys (on many patents from 1896 on).

30 *June*

mechanical analogies

Description of electric circuits in terms of mechanical analogies was at one time very popular. The resonance of an electrical circuit was likened to the swinging of a pendulum, and coupled resonant circuits to two pendulums linked together[39]. Maxwell and his followers even tried for a long time to describe the electromagnetic field in terms of a mechanical model[40]. Tesla's comparison of his "additional coil" to a pendulum is not precisely formulated but rather intuitive. He correctly discriminates between the excitation (initial conditions) and the Q-factor. He does not fully explain how he imagined that the vibrations of the three systems, the primary, the secondary and the "combined system", would be the same. By "freeing" the additional coil he means a weakening of the coupling between it and the secondary exciting it. He obviously had a clear understanding that a circuit can oscillate at its own resonant frequency if the coupling with an excitation circuit is loose.

2 *July*

Spark
spark gap oscillator calculations

Here Tesla gives the calculation of values for the spark gap oscillator in the fullest detail so far. However, the analysis does not include all the magnitudes relevant to the functioning of the oscillator, e.g. the primary/secondary coupling of the transformer and the distributed capacitance of the secondary. The power equation is also not fully explained and justified. However, by means of this approximate calculation Tesla did get a valuable rough guide relatively quickly and easily.

3 *July*

The distributed capacitance of the secondary windings is difficult to determine. It depends on the coil diameter, the dimensions of the wire and the insulation and the winding pattern. In a single-layer coil it is due mostly to the capacity between neighboring turns, and this is the way Tesla calculated it. He considers a greatly simplified model in which it is taken that the parasitic capacity per turn is equal to $A/4\pi d$, where $A = r\pi l$, half the surface area of the wire in one turn, and d is the distance between turns. The capacitance is calculated as that of a plate condenser of area A and gap d with air between the plates. This model is open to a good many criticisms, but it must not be forgotten that Tesla had to find some solution, whatever its shortcomings. It is also not correct that the total inductance and capacitance of the secondary circuit with the "additional coil" are additive, but Tesla was himself aware that this was guesswork, and often mentions the words "roughly", "estimate", etc.

In an earlier calculation (see June 20th) he had started from the primary circuit and worked out the values for the secondary, whereas here he attacks it from the other end:

from the resonant frequency of the secondary circuit and the known primary inductance (one turn) he finds the required capacity of the primary circuit. He then checks whether this capacity can be used with an LF transformer of the given power. The formula is approximate, but gives a good rough guide for the power in the mains transformer. The peak power rating of the transformer must be even greater than the value found because the condenser is not charging all the time but only in short pulses.

5 July

It is possible that Tesla was planning to construct a balloon to take an antenna to great height[13, 14], and was therefore interested in the generation of hydrogen. He does not give any indication, however, of whether he actually carried out any experiments in this direction, or of the grounds he had for expecting the desired decomposition to take place.

7 July

For the "resonance method" Tesla envisaged two possible types of resonant transformer: one with loose coupling between the primary and secondary, and the other with tight coupling but only with part of the secondary inductance*. This latter type he protected under the patent "Apparatus for transmitting electrical energy", for which he applied on 18 January 1902[44]; a good deal of his time at Colorado Springs was spent in developing it.

His conclusions about various parameters of the oscillator indicate that he had by then gained sufficient experience to be able to design such devices with improved performance in the parameters he wanted. As the experiments proceeded he gradually increased the voltage of the LF power supply. On June 20th he had calculated with an excitation voltage of 20 kV, but he had assumed a much higher rate of charging of the condenser, so that he obtained then a greater power than now with 40 kV. The difference in the number of chargings per second is nowhere explained, nor had he ever previously described how it was calculated. The first time he had probably taken it as being equal to the number of breaks on the rotary disharger, and the second time as double the mains frequency. In this light the accuracy of "the capacity of condenser which the transformer will be able to charge" is dubious. However, Tesla did not take the value he calculated as limiting the capacitance in the primary, noting that it did not take into account resonance and other factors which might enable the transformer to charge a much larger condenser.

8 July

From observing the behavior of his oscillator Tesla came to an interesting conclusion concerning the shape of the conductor of the primary winding, i.e. that a strip conductor was better than a wire of circular cross section because all other conditions being the same it did not get so hot. He believed that there was a special reason for this "not yet satisfactorily explained". Since the dimensions of the strip conductor are not known we cannot work out the reduction in resistance relative to a circular section conductor due to the

* It is easily demonstrated that these two methods are similar. If in the second case a part L'_2 of the secondary capacitance is coupled to the primary with a coupling coefficient of k_2, while in the first case the entire secondary inductance L_2 is coupled with a coefficient of k_1, then the response of the secondary to the primary will be the same if $k_1=k_2\sqrt{L'_2/L_2}<k_2$.

skin effect. The surface area of a strip will always be greater than that of a round conductor, the more so the flatter the strip: for a width to thickness ratio of 10 : 1 a strip will have about 1.8 times more surface area; this could effect a considerable reduction in resistance, which would explain, at least in part, the phenomenon which Tesla discovered.

In connection with coils, a problem to which Tesla often returned was that of the velocity of propagation of phenomena through the circuit. In order to achieve the maximum voltage across the secondary terminals without the addition of capacitance Tesla considered that the length of the windings should be equal to a quarter of the wavelength. This would be perfectly correct in the case of a straight conductor with one end grounded. Such a system, when excited, would certainly have the maximum voltage at the free end, but its magnitude would depend greatly on whether the conductor were horizontal (when radiation is small, so that the Q-factor of the resonant system is high) or vertical (when radiation is efficient so that the damping is high). With a helical conductor as in Tesla's oscillator, radiation is low as with a horizontal conductor, so that high resonant voltages are possible unless they are reduced by parasitic capacity. In fact, helical winding increases the distributed inductance and capacitance so that the velocity of propagation of current through the coil is reduced, which means that the wire must be made shorter to achieve maximum voltage across the terminals. If the secondary is terminated with a capacitive load (e.g. a metal sphere) the winding length must be still further reduced in order to maintain the same resonance conditions. Tesla took both these effects into account in designing the secondary.

Fontos helikális tekercs méretezése.

Figures 1—8 illustrate several ways of reducing the distributed capacitance of the secondary. The solution of placing the turns far apart (Fig. 6) is still used today when it is necessary to reduce parasitic capacitance.

9 *July*

In calculating D (the ratio of the turn spacing of the old and new secondary) Tesla accidentally took the frequency instead of the period, so that he got $D=83$ instead of $D=2.45$. A second numerical error occurred in the formula relating D and C (38 omitted from under the square root) so that C came out to be 10 000 cm instead of 227 cm. Since he never made use of these results, Tesla naturally never discovered his mistakes.

Tesla's method of measuring the oscillator frequency by means of an auxiliary coil is interesting. This coil, with its own distributed capacity, in fact constituted an absorptive resonator. The size of the spark across its terminals provided an indication of the amount of power it absorbed. (In some respects it resembled Hertz's resonator). Tesla adjusted its resonance by varying the number of turns for the biggest spark. He then calculated the wavelength on the assumption that at resonance the length of the coil winding was one quarter of a wavelength. The wire length he determined by measuring the coil resistance, the resistivity per unit length of the wire being known. This method embodies a systematic error due to neglecting the reduction in speed of propagation through the coil[45], and it is applicable for oscillators of high power. However, it was the most reliable method Tesla had used to determine oscillation frequency up to that time.

For theoretical calculation of the oscillation period Tesla used two formulae: one which neglects the influence of the secondary (as for example at the beginning of this entry), the other taking this influence into account. In the latter case it is taken that the primary inductance is reduced by a factor $(1-M^2/NL)$, which would be the case were the secondary short-circuited. How far this is justified it is difficult to say because an oscillator which discharges heavily does not satisfy the simple theory of the resonant transformer oscillator: the secondary is then heavily damped and free oscillations in it decay rapidly, so one would have to apply a theoretical treatment for heavily damped oscillators.

10—11 *July*

In order to try and increase the secondary voltage of the HF transformer by keeping down the distributed capacity of the secondary Tesla added a third oscillatory circuit, thus obtaining an oscillator with three resonant circuits of which two are tightly coupled*. The third circuit will not necessarily be most strongly excited when its resonant frequency coincides with that of the primary and secondary (assuming these are the same) and the primary and secondary are tightly coupled. If the spark in the primary circuit lasts long, then the tightly coupled primary-secondary system will produce two distinct oscillations, and the third circuit will be most strongly excited if it is tuned to one (strictly speaking to near one) of these two frequencies. On the other hand, if the spark is of short duration the tightly coupled system may oscillate strongest at the resonant frequency of the secondary, and then the third circuit will be excited the strongest when all three have the same resonant frequency. Tesla believed that his system of coupled circuits was producing a single vibration, which under certain conditions is in fact feasible.

12 *July*

Early on in the diary Tesla mentioned a method using a condenser to store energy from weak impulses arriving at a receiver. In the circuit drawn here, the condenser is charged by a battery via a self-inductance coil and a coherer shunted by the secondary Koherer
of an oscillation transformer. In the absence of an external signal the resistance of the coherer is large so that the charging current is small. The circuit breaker periodically discharges the condenser through the primary of the transformer generating alternating current in the secondary which biases the coherer. When an external signal is received the resistance of the coherer is reduced and the charging current rises rapidly, which in turn increases the AC bias on the coherer which therefore soon gets to full conductivity (in fact there is a feedback loop).

14 *July*

He had tried out the devices shown in these drawings earlier on, some of them for wireless remote control of a boat. Patent No. 613809, "Method of and apparatus for controlling mechanism of moving vessels or vehicles" of 8 November 1898 (application field 1 July 1898) mentions the possibility of using electromagnetic resonance but does not give the circuit diagram of the transmitter referred to here.

15 *July*

Earlier on (see the entry for June 3rd) Tesla presents a general scheme in which the 'dynamo principle" is referred too as one of the ways of accumulating energy from weak

* Similar systems were analyzed in 1906 and 1907 by M. Wien, in 1907 by C. Fischer, and in 1909 by J. Kaiser(46). From their papers it may be seen that the effective value of the current in the loosely coupled circuit will be a maximum if its resonant frequency is the same as that of the other two coupled circuits but if they were loosely coupled.

signals. The circuits given here illustrate how he implemented this principle. The "sensitive device" has a resistance which varies as a function of the antenna signal, and is connected so as to alter the excitation of a DC (Figs. 1, 2, 3) or AC (Fig. 4) dynamo.

Although he says that apparatus using this principle had already worked well in New York, none of these receivers, nor the principle they embody, appeared in any of his patents.

17 *and* 18 *July*

This is a continuation of the work described in the entry of June 12th, with different combinations of the same components plus relay R for registering the signals received. In all the circuits the sensitive device has an accumulating function. He experimented with different modifications trying to optimize sensitivity and reliability. The circuit in Fig. 1 of July 18th has two batteries, and that Fig. 5 an autotransformer instead of the usual transformer with a primary and secondary.

19 *July*

This is the first mention of a device which functions either as a transmitter or, with certain modifications of the power supply and antenna circuits, as a receiver. The transmitter is powered from the mains, the receiver from two batteries, B_1 biasing the sensitive device a with AC pulses obtained by discharge of condenser C through the primary of an HF transformer when the mercury switch closes.

The modification in Fig. 2, in which the relay is the secondary of the oscillator transformer, is simpler, but cannot be used as a transmitter.

21 *July*

In this setup a small excitation of one sensitive device is rapidly amplified by a feedback loop which acts via a transformer on the other sensitive device. Figure 10 shows how the receiver was excited by aerial (elevated metal ball C or C_1) — earth system.

22 *July*

Figure 8 shows the circuit of a receiver obtained by modification of the transmitter Tesla was then experimenting with. When functioning as a transmitter it is powered from the mains and is in fact a standard Tesla oscillator with a mercury interrupter between the condenser C and the primary P. The relay, sensitive device a_1 and battery B_1 are omitted and the secondary is connected to the antenna and ground. It may be noted that Tesla did not use the best receiver modification (as in Fig. 6), probably to simplify reconnection as a transmitter.

23 *July*

The "sensitive device" Tesla used for detecting electrical waves is usually known as a coherer(47). It consists of a tube of some insulator with contacts at either end and metal powder (chips) inside. Its resistance is normally high, but drops rapidly when a large EMF is applied. Munk of Rosenschoeld described the permanent increase of conductivity of a mixture of metal chips and carbon after a Layden jar was discharged through it in 1835. In 1856 Varley noted that the resistance of metal powder was reduced during natural electrical discharges. A major advance was Branly's observation in 1890 that a spark changed the conductivity of a metal powder at a distance. He carried out many experiments with various metal powders, determining their change in resistance by connecting them in series with a galvanometer and battery. In 1894 Lodge* showed that the conductivity of a metal powder could be altered by an electromagnetic wave; this was the final step which preceded the widespread introduction of coherers for the detection of radio waves. From the period 1895—1896 the coherers used by Popov and Marconi are well known.[43, 47]

Once activated, a coherer remains in the conducting state. To reestablish the high-resistance state it has to be shaken. The strength and timing of the shaking have to be properly adjusted. A novel method of decoherence of powders was invented by Popov, and used by him in his receiver and later by others[43]. In 1898 Rupp[48] found that constant slow rotation of the coherer keeps it sensitive. The decohering effect of rotation had been discovered earlier, in 1884, by Calzecchi-Onesti[49].

Tesla mentions that he had worked with a rotating coherer in the New York laboratory, so it is possible that he used decoherence by rotation before Rupp. He finds it superior to other methods of decoherence, because then the sensitive device behaves like a selenium sell, conducting only when radiation acts upon it. Also its sensitivity can be controlled by changing the rate of rotation.

24 *July*

From the pagination of the manuscript it may be seen that the entry for this day was divided into three parts (the previous day two parts). The first part, three pages, refers to experiments with a 35-turn secondary on the oscillator, the second part, five pages, to a resumption of these experiments, and the third, three pages, to the determination of the capacity of the 35-turn secondary.

Tesla adjusted the regulating coil in the primary to obtain the maximum secondary voltage, judged by the size of streamers. He connected an "extra coil" to the free terminal of the secondary. He investigated the operation of the transformer at harmonic frequencies by doubling the primary capacity** and making fine adjustments of the primary frequency by varying the inductance in order to get maximum response of the secondary to the harmonic of the primary.

On resuming the experiments Tesla sought an explanation for the occurrence of the largest streamers from the secondary when the regulating inductance was practically cut out. He found it confusing that the highest voltage at the free terminal of the extra coil (connected to the secondary like in Fig. 2 of July 11th) was not obtained when the frequency of the excitation was equal to the natural resonant frequency of the coil. After an extensive analysis he came to the correct conclusion (unlike that of June 30th, which was valid only for a special case), that when free oscillation of the secondary becomes influential, the parameters of the primary have to be adjusted to get maximum voltage across

* The term "coherer" is due to Lodge, and denotes a device containing particles of metal such that its resistance is normally high, but is reduced under the influence of electromagnetic radiation.

** For the primary to oscillate at half the frequency the capacity would have to be quadrupled. It is possible that instead of connecting the banks of 8—9 jars in series, equivalent to the capacitance of 4—4 1/2 jars, Tesla connected the previously series connected jars in parallel, achieving an equivalent of 16—18 jars, i.e. four times the capacitance of the series configuration.

the secondary, and resonant frequency of the extra coil has to be equal to the resonant frequency of the coupled primary-secondary system. It seems that it did not occur to Tesla that when the coupling was tight the combined system produced different spectra during and after the spark. It would seem therefore, all the more significant that he was able to reach this correct conclusion, through a combination of empirical results, simple theory and intuition.

Tesla notes that during discharge in the secondary sparks went across the lightning arresters. Since the arresters were connected to the power line, Tesla thought that the HF voltage came from a wave propagating through the earth and getting into the line somewhere else. We have no evidence which would support this statement or establish whether it was not due to coupling between the oscillator and the mains via the power transformer.

The third part of this entry refers to measurement of the capacity to ground of the secondary coil as a whole. Tesla does not explain how he performed the comparison with a standard capacitor nor at what frequency.

26 *July*

This entry is concerned with much the same topics as that of June 30th. He investigated the influence of the HF transformer primary-secondary coupling on the 8th of July.

27 *July*

In his first condenser discharge oscillation transformer for generating high frequencies in 1891[4, 15] Tesla used a simple air gap for regulating the charging and discharging of the condenser. However, a year later he had already described several improvements on simple spark gaps using a magnetic field or an air current for rapid extinction of the arc thereby reducing the period of the charge-discharge cycle. He also described the advantages of a splitted arc across several smaller air gaps: with the same total gap length the breakdown voltage is higher, so that smaller gaps can be used and the losses are less*. A fourth form of improvement which he invented was the use of various rotary interrupters[5].

In the period from 1893 through 1898 Tesla patented several types of interrupter, or "electric circuit controllers". It is interesting that all these patents refer to various types of rotary interrupter, with or without an air gap. Some rotary interrupters were protected within patents for high-frequency generators, including the following:

the combination with discharge points immersed in oil. The turbine whose blades make and break the condenser circuit is driven by oil under pressure[50]

mechanical make-break controllers for DC[51]

synchronous controllers with and without regulation of the interrupt timing, for use with AC sources[52]

commutators for alternate switching between two condensers in the primary circuit of a Tesla oscillator[53].

In 1897 and 1898 Tesla was granted a number of patents for "electric circuit controllers". The principle requirement was that they should make and break a circuit at the highest possible rate, i.e. that they should perform a large number of operations per unit

* The total resistance of series air gaps is less than the resistance of a single air gap with the same breakdown voltage.

time. In eight patents[27] Tesla gives designs for rotary interrupters with conducting or conducting and insulating fluids, usually mercury and oil, respectively. In some designs the interruption takes place in an inert gas under pressure. He gives ingenious designs for using a mercury jet playing on a toothed metal rotor, and for producing two mercury jets (fluid contact).

The rotary interrupter with two auxiliary air gaps shown in the figure was a new idea. One of the reasons Tesla added these air gaps was probably the high voltages with which he was working, since they allowed him to regulate the excitation. That this could be done may be seen from the statement that by adjusting these gaps the period of charging from the secondary of the mains transformer could be shortened. At the end of the entry he records that the best results were obtained with two rotary interrupters (with toothed disks) rotating in opposite directions. He does not explain how he chose the tooth ratio so that the number of interruptions was equal to the product of the number of teeth.

28 *July*

This entry provides one of the most detailed descriptions of the receiver with two rotating coherers and a condenser for accumulating the energy from weak signals. At point *b* the circuit *C—P* is periodically made and broken and the resulting AC pulses bias sensitive device *A'* in the secondary. Sensitive device *A* is still poorly conducting so the charging current of *C* via damping coil *L* is small. When an arriving electromagnetic wave reduces the resistance of *A*, *C* charges much faster and the voltage induced in secondary *S* also rises rapidly. The resistance of *A'* drops rapidly and current from battery *B'* activates relay *R*. Judging by Tesla's report, the receiver was very sensitive to distant electrical discharges.

29 *July*

To check out his theoretical conclusions about the free oscillation of the "extra coil" (see 30 June and 26 July) Tesla made a new coil with a higher inductance. As this was his first experiment with the new coil, he had to adjust the circuit parameters by trial and error.

Tesla's ingenuity found full expression in the way in which he developed condensers for high voltages. He filed a patent application on his design for a fluid electrolyte condenser on June 17th 1896[67].

30 *July*

To try and verify his hypothesis about the rejection of harmonics with appropriate coils, Tesla changed the connection of his "extra coil" as shown in Figs. 4 and 5. To understand his way of proceeding one must take into account his ideas from 1893[6] concerning the induction of earth currents via an aerial-earth system. However, the standing waves in terms of which he tried to explain the arcing over the lightning arresters cannot be significant at these frequencies.

31 *July*

Tesla made the condensers for the primary circuit out of mineral water bottles filled with a saturated solution of rock salt, and standing them in a metal tank of the same solution, thus creating a condenser bank with one common plate. The other plates (the electrolyte in the bottles) could be connected in parallel as desired. The smallest capacity adjustment possible was equal to the capacity of one bottle.

After various tests of what voltage the glass dielectric of the bottles could stand, Tesla returned his attention to the secondary of the oscillator, in which rightly way the limiting factor for obtaining higher voltages. His analysis of the distributed capacity of the secondary is a good illustration of his inventiveness in a little known field and how he sought to reduce problems to a simple but mathematically and physically sufficiently accurate model. It must not be forgotten that these are Tesla's working notes, which is sufficient justification in itself for some of the hypotheses which the reader might otherwise rightly object to.

2 *August*

A receiver of this type is mentioned in the entries of July 12th (the principle), July 28th (circuit diagram with two sensitive devices and relay), July 30th (in connection with earth waves). The transformer here has a frame similar to that of July 28th but with somewhat more turns. The sensitive device was described on July 21st.

Tesla often worked on several problems in parallel. Here for example we have entries concerning the receivers, the development of condensers for the primary of the big oscillator, and the power equation for a new configuration of the oscillator primary circuit. The condenser C_1 in Fig. 2 protects the mains transformer against overload but has the drawback that it reduces the initial voltage on C_2. Tesla's analysis refers to the case of two condensers in series, neglecting all transient phenomena. It may be that he was induced to think about protecting the mains transformer because of his doubts about the ability of the dielectric to stand the voltages which he intended to use.

3—14 *August*

These experiments are a continuation of some earlier research. Here Tesla investigates various modifications of his "condenser method of magnifying effects". All the circuit diagrams of receivers, over 50, include at least one battery, sensitive device, condenser, rotary interrupter and HF transformer. Some of them show a relay for registering the signal received, while in others its presence is understood. Likewise, in all except one case (5 August, Fig. 1) the plates which brings the excitation to the sensitive device are not shown. Tesla says that these plates can be in one or two media, meaning that both can be in the air, both in the ground, or one in the air and the other in the ground, preferably elevated. In the patent[8], referring to these plates, he also says: "... they may be connected to conductors extending to some distance or to the terminals of any kind of apparatus supplying electrical energy which is obtained from the energy of impulses or disturbance through the natural media."*

As regards mode of operation, the various receivers have in common that the sensitive device is biased by a battery. They also include a Tesla oscillator (clockwork rotary interrupter) which creates an added bias on the sensitive device (or devices). This AC pulse bias acts as positive feedback, avalanching the sensitive device into conduction as soon as an arriving signal starts to cause some change. In the receivers with two sensitive devices

* It is interesting to note a similarity of such receiving system and the contemporary ELF grounded wire radiator. In the Nikola Tesla Museum in Belgrade few drawings, showing something that resembles a single grounded wire radiator and a parallel array ELF antenna[72], are found.

the one which receives the external signal is usually in the primary side and the other, which activates the relay, on the secondary side. When there is only sensitive device it usually shunts the transformer secondary (which has a high impedance so as not to reduce the performance of the device), thus creating an efficient feedback loop.

A general feature of all Tesla's receivers is their delicacy. Very careful adjustment was necessary to get the sensitive device at the threshold of avalanching. Most of the sensitive devices were rotated (see June 23rd) so that they were only good conductors during the action of a signal. In some cases, however, this did not achieve satisfactory deactivation of the coherer. Then he used an electromagnetic buzzer to periodically interrupt the excitation of the sensitive device (see Fig. 2 of August 8th). Probably the circuit in Fig. 2 gave him the idea for that in Fig. 3, where the rotary interrupter is replaced by a buzzer as an electromagnetic interrupter. He then used a buzzer in various other configurations (Figs. 5 and 6 of August 8th), with the aim of reliably biasing the condenser, and hence also the sensitive device, to threshold.

Tesla did not measure the sensitivity of his receivers by any definite method, but there is no doubt that he did compare them in some way. From his notes very little can be deduced about their sensitivity, i.e. the power required to activate them. A rough idea is given by data from July 4th, when he used similar receivers to register electrical discharges. He estimated that he registered waves produced by lightning at least 200 miles away, and continued to receive signals (at periodic intervals) later when the weather had already cleared. He records that with the receiver shown in the figure of July 28th he was in one instance able to register lightning discharges at a distance of 500 miles. He estimated the distance from the periodicity of the signals as the storm moved away.

13 *August*

The last experiments with the oscillator were described July 31st, with numerous comments and the remark "this to follow up". Probably he had prepared a new condenser bank in the meantime for work with higher voltages (he measured the capacitance of the new bottles on August 11th, and tried them out with the highest voltage so far from the power supply transformer.

15—21 *August*

With the new condenser bank the secondary had to be modified, and on August 15th he worked out the length of wire required. He calculated the period of the primary from the capacity of the new bottles and the inductance per turn of the primary found earlier (mentioned on June 20th as 7×10^4 cm, probably one quarter of the value measured for two turns on June 17th). It was also his intention to adjust the oscillator to the "extra coil".

The entries for 16, 17, 20 and 21 August give some new circuit diagrams for the oscillator which he thought would be more suitable for working at high excitation voltages. They bear witness to Tesla's constant search for improvements involving only limited changes in the apparatus which he used for lower voltages. The chief problem was overloading of the power supply. It is recorded elsewhere that Tesla's experiments with his spark oscillator (probably on some other occasion) burnt out the generator of a power station five miles away[36].

22 *August*

In this entry he returns once again to the receivers. He tried out two receiver circuits using one battery and one sensitive device. He changed the capacity in the primary circuit over a wide range, but it is not clear why 1 μF proved best. It remains unexplained what was the relationship between the frequency of the incoming signal and that generated by the receiver itself. Could it perhaps be, if the rotating coherer behaved as a nonlinear element, that the signal was amplified as in a heterodyne receiver[55]?

2 milli Volt!

23 *August*

He now put the extra coil in the center of the primary, retaining this configuration from then on. After the usual adjustment of the oscillator he got sparks 2 m, and later 4 m long, indicating a voltage of around 2 million volts.

26 *August*

Tesla experimented with twice the interruption rate. The oscillator worked better and there was heavy sparking across the lightning arresters (Fig. 4). Investigating the cause of this sparking he inserted a coil in the lead of the metal sphere (Fig. 1) to reject high frequencies. In an earlier experiment (see July 30th) inserting such a choke coil in the ground line had stopped sparking across the arresters. This time it did not, so Tesla tried the circuit in Fig. 2. Still there was no marked change, the sparking across the arresters was only slightly reduced. After this experiment he began to wonder whether the grounding point of the secondary was not perhaps a peak rather than a node of the standing wave. It must be understood that Tesla thought that standing waves were set up around the transmitter (like waves on an open transmission line. With shorter waves the rate of change of amplitude with distance would be faster (i.e. maxima and minima would occur at shorter distance intervals), so he thought that a large potential difference could be obtained with a short distance between the grounding of the secondary and that of the lightning arrester.

Static induction!

In order to explain what happened when the sphere was not grounded (which would mean that there were no short waves) but the sparking across the arrester did not stop, Tesla found it necessary to formulate a new hypothesis: "Could the sparks be produced by static induction upon wire through the air and not chiefly by conduction through earth?" The experiment with which he tried to verify this hypothesis did not yield any definite answer.

27 *August*

Although he has noted several times already that good results were obtained with various decoherence techniques (rotation, interruption of the excitation current), this reexamination of his old ideas shows that Tesla is still seeking a more reliable solution. One of the ideas he was gathering together for further investigation is illustrated by the diagram in Fig. 4, in which a rotary interrupter, condenser, choke and battery provide bias for the sensitive device. When interrupter *d* breaks, the voltage on *C* can be higher than the battery voltage. With proper choice of the values the coherer can be biased to threshold, making it very sensitive.

28 *August*

Tesla's idea of the Earth as a perfectly conducting sphere lead him to a mistaken hypothesis about the general behavior of the electromagnetic field around the grounding of the transmitter. What he expected at frequencies of the order of 10 kHz in fact occurs at much lower frequencies[72], at which, as far as can be seen from his notes, he did not work in Colorado Springs. He correctly observed that the decisive factor determining whether predominantly waves of the "Hertzian type" or the waves which he thought to be propagated through the earth (in fact waves in the spherical condenser constituted by the Earth and the ionosphere) would be excited was the excitation of the "Earth". Tesla was also certainly in error when he tried to make generalizations concerning the wave frequency, and in his conviction that he needed extremely high voltages to "create" the second conductor for a system of wireless power transmission. He could not know that this conductor already existed permitting transmission at very low loss of very low frequency waves, and that it would not matter whether the energy transmitted was high or low.

29 *August*

Although the circuit looks simple enough, an analysis of Tesla's receiver with a "magnifying effect" is rather complicated, because transient phenomena have to be taken into account and the resistance law of the sensitive devices as a function of voltage has to be known. It was not easy to adjust a receiver like this to work properly.

Apparently there was an earphone T in the secondary circuit of the transformer, but it is not mentioned in the notes. The sensitivity of an earphone would normally be much greater than that of a relay, so it would be interesting to find out how this apparatus performed. Unfortunately, earphones are practically not mentioned anywhere in the diary.

Tesla here at last makes a few remarks about how the sensitivity of receivers was estimated. To test its response he put a "small capacity" across sensitive device a, but of what value, and whether it was charged or not he does not say.

3 *and* 4 *September*

The aim of these experiments is not explained, but it was probably associated with the "experimental" coil with which he examined currents in the water pipe. This was a resonant coil which in the receiver played a part analogous to that of the "extra" coil in the transmitter. Its purpose was to maximize the received signal. Since Tesla connected one terminal to ground, it appears that he wanted to pick up electrical vibrations from the earth. In this case too he found that it was not sufficient just to increase the Q-factor $\frac{pL}{R}$, but also that it was necessary to keep the coil's distributed capacity as low as possible. This conclusion was consistent with what he had earlier found about the influence of distributed capacity of the coil on the length of wire needed to achieve resonance. Conclusion (5) is interesting in that it shows Tesla was aware that the secondary and the extra coil, although excited by the same primary, would each oscillate at its own resonant frequency, and if these were not the same, they would beat.

5 *September*

After a number of experiments, including a few outside the laboratory, Tesla once more concludes that parasitic capacity is very harmful, so he decides to try winding a coil to have minimum capacitance. Unfortunately he does not describe how this was done. In his desire to get the maximum possible voltage from the coil he went as far as thinking that it was best to have no capacity at the free terminal. From one aspect he was right (theoretically a coil gives the highest Q-factor with the least capacity in the resonant circuit), but without the "elevated" metal sphere the received signal was much weaker because the free terminal of the coil no longer had a monopole antenna. In the circuit which he in fact used he did not, however, go to such extremes. He added the "experimental" coil but left the metal sphere (aerial capacity) connected to one end of the sensitive device.

6 *and* 7 *September*

In calculating the wavelength for the cable and ball Tesla made an arithmetical error. For the calculated *T*, the wavelength ought to be about ten times less, so that his assumption that on September 7th, he got vibrations of the system consisting of a ball of capacity 38 cm and 120 feet of cable is probably false. It is more likely that the experimental coil was excited by the coupled system of primary, secondary and extra coil.

11 *September*

Tesla probably thought that he would more easily detect standing waves in the vicinity of the laboratory if the wavelength was shorter. He assumed that the ball-cable system would produce waves which could be registered by the receiver. However, although he measured the electromagnetic field up to a mile away, he probably did not find the expected variation, and could only conclude that electrical disturbances were registered.

13 *September*

From a document found in the archives of the Nikola Tesla Museum in Belgrade it may be seen that Westinghouse Comp. sent Tesla a 50 kW power transformer for a primary voltage of 200/220 V and secondary tappings of 40, 50 and 60 kV. This is probably the Westinghouse transformer which he often mentions.

15—17 *September*

The receivers described on September 5th, Fig. 3, and September 11th, Fig. 2, include "tuned" coils whose function is similar to that of the "synchronized" coils shown in the diagrams of September 15th. Tesla did not make a detailed analysis of these receivers, nor do any of his patents on receivers refer to similar circuits. It therefore seems that we do not have sufficient information to draw any reliable conclusions about their sensitivity or their ultimate purpose (for example it is not clear whether they are just for registering signals or for receiving intelligence).

18 *and* 19 *September*

As already remarked, oscillators like those he was working with here are not the classical Tesla oscillator with a resonant transformer. The "extra coil" essentially changes the loading of the secondary circuit, and this alters the mode of oscillation. Also, shunting the secondary with capacitance (as in the diagrams of 18 September and 19 September Figs. 2, 3 and 4) alters the spectrum of the oscillation in comparison with that yielded by an oscillator with two oscillatory circuits. Configurations such as those shown in Figs. 5 and 6 of September 19th can be considered as typical Tesla oscillators with a loosely coupled third circuit consisting of the extra coil and capacitive load. Then the greatest voltage at the free terminal of the extra coil is obtained when the natural resonant frequency of this circuit (together with the ball antenna) is the same as that of the strongest component in the spectrum of the oscillator.

22 *and* 23 *September*

Having investigated the tapering secondary Tesla started making a new, 15 m diameter cylindrical secondary. The criterion that the weight of copper in the primary and secondary should be the same follows from the requirement of equal losses in the two windings (losses in the copper). This way of calculating the gauge of the primary and secondary conductors is applied in designing LF transformers, but for HF transformers it only provides a rough guide, for a number of reasons, e.g.: the current ratio may differ considerably from the turns ratio, skin effect is not taken into account, etc.

25 *September*

As he often did earlier, before finalizing a set up Tesla measured the inductance of the primary and the regulation coil which he usually used as an added, adjustable primary inductance. The value he obtained for L_{2p} differs from that obtained earlier (see July 17th) by the same method.

26 *September*

By this method the frequency of an oscillator is found with a help of a resonant circuit of known parameters. When its resonant frequency is adjusted to coincide with the frequency of the oscillator, the voltage across its terminals, estimated by the strength of the spark across an "analyzing gap", is a maximum. Tesla says that the excitation must be "convenient". Since he introduced regulation of the excitation by means of the small gap b, it is clear that "convenient" excitation was obtained with loose coupling. Loose coupling between the primary and secondary circuits of a spark oscillator ensures that the two frequencies which such an oscillator normally produces are very close. Up to a certain degree of coupling, Tesla's oscillator produces a single frequency. According to Fleming and Dyke[31], with an ordinary spark gap the maximum coupling coefficient for monochromatic oscillation is around 0.05 (certainly less than 0.1), while with a rotary break producing pulse excitation a coefficient of up to 0.2 gives good results. With higher coupling coefficients three components are obtained, even if the primary and secondary circuits by themselves have the same resonant frequency.

27 *September*

True to the principle that measurements should be checked by calculation, Tesla calculates the inductance of the same coil using the formula for a coil of infinite length, but does not obtain agreement. Since distributed capacitance increases the effective inductance at frequencies below the natural resonance of the coil, the second possible reason which he mentions (inexactness of the coil dimensions) could have some influence, but the main reason is the poor approximation provided by the formula when applied to a coil with this length: diameter ratio.

28 *September*

The circuit diagrams are of great interest because they illustrate a new approach to feeding the antenna (now known as shunt feed[73]) which obviates the problem of insulating the aerial pole. Unfortunately the explanations Tesla gives are too cryptic to be fully comprehensible. The figures do not clearly show whether the lower terminal of the antenna is grounded or insulated. Tesla's conclusions that a standing wave is set up along the antenna and that the distance between points of equal potential is half a wavelength are correct.

The frequencies he was using were not high enough for his antennas to work in the manner shown by the figures (in which case they would be much more efficient radiators than he usually had), so that this contribution to the theory of wire antennas was never properly formulated.

29 *September*

Tesla says that he experimented with the antennas shown in the drawings, but he does not compare them with a grounded antenna.

The shortness of the antennas relative to the wavelength made them inefficient radiators. The configuration shown in Fig. 3 was best probably because it had the greatest terminal capacity, providing the most favorable current distribution on the antenna. Lack of coil and ball dimensions makes it impossible to go into any more detailed analysis of these antennas.

3 *October*

high frequency oscillator

The drawing of several of the coils which Tesla often used offers some interesting information about the laboratory which cannot be seen from the numerous photographs. One sees that there was a wooden floor raised 30 cm above ground level, and the drawing shows the dimensions of the coils and how the HF transformer of the oscillator was wound.

4 *October*

Tesla was primarily interested in the change of capacity of a ball with height, so he measured the primary capacity for two elevations of the ball. In both cases he tuned for resonance of a "special coil". In the first measurement he had $L_p C_{p1} = L_{sc} C_{b1} = 1/\omega_1^2$ and in the second $L_p C_{p2} = L_{sc} C_{b2} = 1/\omega_2^2$, where p refers to the primary circuit and b to the ball. These equations neglect the effect of interaction between the primary and secondary. They readily yield Tesla's equation

$$\frac{C_{p1}}{C_{p2}} = \frac{C_{b1}}{C_{b2}}$$

The inductance of the primary L_p and of the "special coil" L_{sc} do not figure in the capacity ratio equation. In deriving this equation all distributed capacitance in the secondary and the secondary coil itself are neglected.

6—8 *October*

From the measured inductance of the new secondary and mutual inductance of the primary and secondary, and the primary inductance measured earlier (see September 25th), it follows that the coupling coefficient was 0.58, i.e. tight coupling*. An oscillator with this much coupling will probably produce three pronounced components, even with very rapid interruption of the spark in the primary; this is indicated by the results Tesla obtained with spark oscillators with looser coupling (see the commentary on 26 September).

As before, Tesla determined the wavelength of the oscillator from the period of the primary circuit (see, e.g., June 20th). He compares one quarter wavelength with the total length of wire in the secondary, special coil and extra coil (when no other coils were used, he considered that the length of the secondary windings should be one quarter wavelength).

9 *October*

He made the last measurements of the change of capacity of a sphere with height on October 5th, but did not give the calculation results. He subsequently improved the apparatus as a whole and in the present entry describes a different way of connecting the "special coil", the chief effect of which was to loosen the coupling, which immediately proved its advantages. With weaker excitation it was easier to adjust the "special coil" to resonance because there were no streamers. Parasitic capacities were reduced, mainly to the distributed capacity of the "special coil".

Tesla first determined the distributed capacity of the "special coil". He assumed that the ball circuit resonated at ω_0, determined by the primary circuit, so that one can write

$$L_{p1}\, C_p = L_{sc}(c + C)$$

where L_{p1} and C_p are the total inductance (including the regulating coil) and capacity of the primary circuit, L_{sc} is the inductance of the "special coil" (including connecting wires), C is the distributed or parasitic capacity of the "special coil", and c the capacity of the ball.

Subsequent changes in the height of the ball changed the capacity in the circuit of the "special coil". To bring the oscillator into resonance with this circuit again, Tesla changed the inductance in the primary circuit. When resonance is achieved, according to Tesla, one can write

$$L_{p2}\, C_p = L_{sc}(c' + C)$$

Dividing this by the preceding equation yields

$$c' = \frac{L_{p2}}{L_{p1}}(c + C) - C$$

which is in fact the equation Tesla uses to find c'. Because of an arithmetical error in calculating C, Tesla's numerical results for the ball capacity are about 10% higher than they should be, but this does not essentially affect the conclusions. To calculate the distributed capacity of the coil** he uses the relation $L_pC_p = L_{sc}\ (C + c)$ for the ball at

* The regulating coil in series with the primary reduced the coupling. The new coupling coefficient is found to be $k' = k\sqrt{L_p/(L_p + L_{rc})} < k$.

** By distributed capacity Tesla used to mean the total capacity between turns of the coil. Here he uses a different definition of "internal capacity" similar to that normally used today.

a height such that he could consider its capacity close to the theoretical capacity of an isolated sphere.

11 *October*

Tesla obviously did not sleep much the previous night since he was photographing the oscillator in operation both late at night and early in the morning. The Nikola Tesla Museum in Belgrade possesses several photographs which date from this period, but they are too faded to be worth ~~showing. One of the~~ better preserved photos is shown on p. 221.

12 *and* 13 *October*

To calculate the inductance of cylindrical coils Tesla used the formula for a coil of infinite length, which always gave values too large, especially when the diameter: length ratio of the coil was not much less than unity. However, when the proper corrections are made (Russel[57]), the inductances obtained differ from Tesla's values by less than one percent.

15 *October*

Because of the arithmetical error made on October 9th (see commentary), he mistakenly concludes that the capacities of the ball are now somewhat less than before. Had he used the correct values, his conclusion would have been just the opposite.

17 *October*

The 122 ft metal pole bearing the 30" ball is the antenna to be seen in the middle of the laboratory on many photographs. The bottom end of the antenna is insulated by a wooden pole. This is a single-pole antenna of small electrical length. At around the highest frequencies which Tesla used the h/λ ratio was about 0.015. The terminal capacity made the effective height somewhat greater than h, but it still remained an electrically short antenna.

20 *October*

Tesla was measuring the capacity of the coil which he had used for determining the change of capacity of a sphere with height (up till October 9th he had called it a "special coil"). Considering the dimensions of the primary (coil diameter 15 m) and the coil being tested (diameter 64 cm, length 145 cm), the coupling between them was obviously loose, so that the frequency found from the parameters of the primary circuit (provided that the main secondary of the oscillator did not influence the oscillation of the primary) can now be accepted as accurate. It is not stated how resonance was determined, but it was probably from the sparks at the terminals of the test coil. Similar resonance methods are given in recent textbooks on electrical measurements[56]. It must be noted, however, that determination of the distributed capacity of a coil from the resonance of the coil alone is not reliable, it depends on the mode of excitation and always gives lower values. It is therefore recommended to measure it with an added lumped capacity in the circuit.

21 *October*

In a thorough analysis of all details of his measuring apparatus, Tesla did not omit a determination of the parasitic inductance of the connections, by an interesting method which he says he used often in the New York laboratory. Varying the primary inductance and capacitance but keeping a constant frequency of the oscillator (as determined with an auxiliary resonant circuit), one has

$$C_{p1}(L_{p1}+L_{con}) = C_{p2}(L_{p2}+L_{con})$$

where C_{p1}, L_{p1} are the first and C_{p2}, L_{p2} the second capacitance-inductance pair in the primary giving the same frequency. From this equation one can find the parasitic inductance of the connections L_{con}, which Tesla denotes by x.

23 *October*

In further experiments to determine change of capacity with height Tesla uses an apparatus similar to that of the previous day. As far as can be judged, the coupling between the oscillator and the measuring circuit (coil with elevated ball) was loose. The lower terminal of the latter was connected with a condenser of the oscillator circuit. Loose coupling is evidenced by the relatively weak sparks obtained across the air gap of coil L (see figure) in comparison with the sparks obtained when a similar coil was excited by the secondary of the oscillator, tightly coupled to the primary (as for example on October 4th and 5th). Under these conditions the spark oscillator would generate a single frequency, determined by the parameters of the oscillatory circuit with the spark gap.

26 *October*

Tesla had already been using the 689-turn coil for several days in experiments to determine change of capacity with height of a ball. On October 18th he calculated its inductance using the formula for an infinitely long coil. Now he determines it by measuring the current and voltage at a frequency of about 140 Hz, knowing the resistance. He gives the results of two sets of measurements. He is convinced that the second set, for which he used a small dynamometer, gave low values, and this was probably so. The first set gave an inductance slightly less than calculated, but a correction of the theoretical value for the finite D/l ratio* gives a value about 6% less than that measured. Thus the calculated value ought to have been 0.023 H, while the experimental result was 0.024 H. The accuracy of the measurement method cannot now be verified but in view of the small difference between reactance and resistance it is doubtful whether it could be of the order of a few percent.

27 *October*

Tesla does not explain how he made the comparison with a standard 0.5 μF condenser. The number of bottles used in the condenser bank is indeed impressive. He did not

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* Russell[57] gives the inductance of a coil at very low frequencies as

$$L = (\pi Dn)^2 l\left[1-0.424\frac{D}{l}+0.125\left(\frac{D}{l}\right)^2-0.0156\left(\frac{D}{l}\right)^4\right]$$

Substituting $\pi D^2 = 4S$ (D is the mean diameter of the coil), and $n = N/l$ (number of turns per cm), the first term in the above equation yields the expression Tesla used. l is coil length. When all quantities are expressed in units of cm, L is also obtained in cm.

carry out measurements on individual bottles to determine what kind of tolerance they had. Since he only measured complete banks, i.e. rather large capacities, and mentions "readings with 7 cells battery", he probably made the comparison in terms of stored charges.

28 *October*

After several days gathering data and making further measurements of inductance and capacitance, he finally proceeds to the calculation of the unkown capacity of the sphere, using the readings of October 23rd and 26th. Consistent with his general principle, he checked the measured values by (usually approximate) calculations.

He calculates the capacitance of the vertical wire by the formula for an isolated ellipsoid of high eccentricity. It is not known whether Tesla first had the idea of using this formula, but it was used later for a similar purpose[58]. All things considered, the agreement between the calculated and measured values is very good.

Tesla then calculated the ratio of the capacities in the lowest and highest positions. In the lowest position the sphere makes little difference to the total capacity. In the highest position it increases the capacity in the coil circuit by 18.7 cm. This is less than the theoretical value for an isolated sphere of 18" diameter, which does not agree with some of his earlier measurements (see the results of October 21st for a 30" ball). However, if a comparison is to be made, it must be noted that the new results are probably better because the apparatus had been modified and the parameters checked.

29 *October*

His remark about eddy currents in the sphere is interesting. To prevent their formation he slit the tinfoil with a knife. Did he assume that in the vicinity of the coil the sphere would behave like a short-circuited turn? It is readily shown that if this effect is pronounced (and not taken into account) the measured capacity of the sphere will be too low. This might be an explanation for the reduction of the effective capacity of the sphere in the lowest position (see the calculation of October 28th for an 18" sphere in the lowest position).

1 *and* 2 *November*

The new extra coil was larger in diameter but shorter than the previous one (see August 23rd). The formula for an infinite coil introduces a rather large error, but with the correction referred to in the commentary to 26 October the agreement with the experimental results is good. The correction terms are significant because the ratio D/l is even greater than unity, and the correction is more than 30%. The corrected value is 0.0198 H, 2—3% less than the measured values.

3 *November*

A repeated measurement of the capacity of the vertical wire and the 30" sphere by the method of October 29th but with a new coil L (see October 31st). A new feature is Tesla's attempt to eliminate the wires of the spark gap, estimating the excitation solely from the streamers.

5 *November*

Photographs of the Colorado Springs laboratory always show the pole rising from the center of the building. Its dimensions are given in the entry of 17 October. Now Tesla calculates the capacity of the pole as the sum of the capacities of its parts of different thickness, using the formula first cited on October 28th. His final remark indicates that he had thoroughly understood the physical essence of the phenomenon.

6 *November*

Tesla carefully measured the capacitance of the aerial pole by the resonance method, from the known inductance of the 550-turn coil (see September 8th) and known frequency of the oscillator, with two measurements, one with and the other without the capacity to be measured. He did not make use of his earlier results for the inductance of the regulating coil and connections from October 30th, although he could have done. A calculation check shows that the results of October 30th were rather high (by as much as 10% for $2\,{}^1/_8$ turns of the regulating coil), but Tesla probably thought that the new procedure was better and so did not use the old results. An analysis shows that if the old values had been used the final result would not have been essentially affected, so that Tesla's conclusion that the measured capacity of the pole was less than the theoretical value of November 5th remains valid.

From the relatively lengthy discussion following the measurements it may be seen that Tesla expected just the opposite. As usual when his expectations were not fulfilled, he considers ways for getting more reliable results.

7 *November*

Measurement of the capacity of the structure at two frequencies was intended to demonstrate the reduction of effective capacity with increasing frequency. Tesla did in fact obtain a small difference, but it is dubious proof considering the accuracy of the measurements. The frequency difference was quite large, from 50 kHz to nearly 250 kHz (using "extra" and "experimental" coils).

8 *November*

The primary inductance values cited are from November 5th. The other values given in the table do not agree with those derived from the measurements of October 30th. Also, earlier data do not include values for half a turn of the regulating coil. It must therefore be concluded that the measurements from which the tabulated values were calculated are not described in the diary.

It seems that in measuring inductance from voltage, current, frequency and resistance Tesla had difficulty because of unreliability of the frequency determination. He therefore used the voltage ratio, when it is only necessary for the frequency to be constant. By this method he measured the inductance of the regulating coil plus connections, for various numbers of turns.

9 *November*

The measurements of mutual inductance in terms of the inductance of the primary when the secondary is open and short circuited are noteworthy. They were made at constant current and frequency, simplifying the calculation.

To reduce the oscillator frequency, in some cases Tesla used two special coils which he refers to only by wire gauge number. He compares the calculated and measured values for these coils. The values measured by the voltage ratio method are about 2% less than those found from voltage, current and frequency. The calculated values are lower than either. Correction of the measured values as described in the commentary to 26 October does not make much difference (about —5%) because the D/l ratio is relatively small.

10 *November*

Had Tesla published the measuring methods he developed in New York and Colorado Springs, his name would probably be frequently encountered in earlier textbooks and handbooks on electrical measurements at high frequencies. As it is, we can only remark his exceptional ingenuity in designing measuring devices and the accuracy with which he determined the resonance of oscillatory circuits. An especially interesting feature is his method using a lamp already heated up by a supplementary power source, greatly increasing its sensitivity to small amplitude changes around the resonance peak of the oscillatory circuit.

11 *November*

In measuring the capacity of a sphere at different heights Tesla here uses a loosely coupled circuit containing a lamp to determine resonance. The results for a 50 ft wire differ somewhat from those of October 28th, but are within the limits of error of the method. The values for the capacity of the sphere are somewhat higher than before, but not in proportion to the diameter of the sphere.

12 *November*

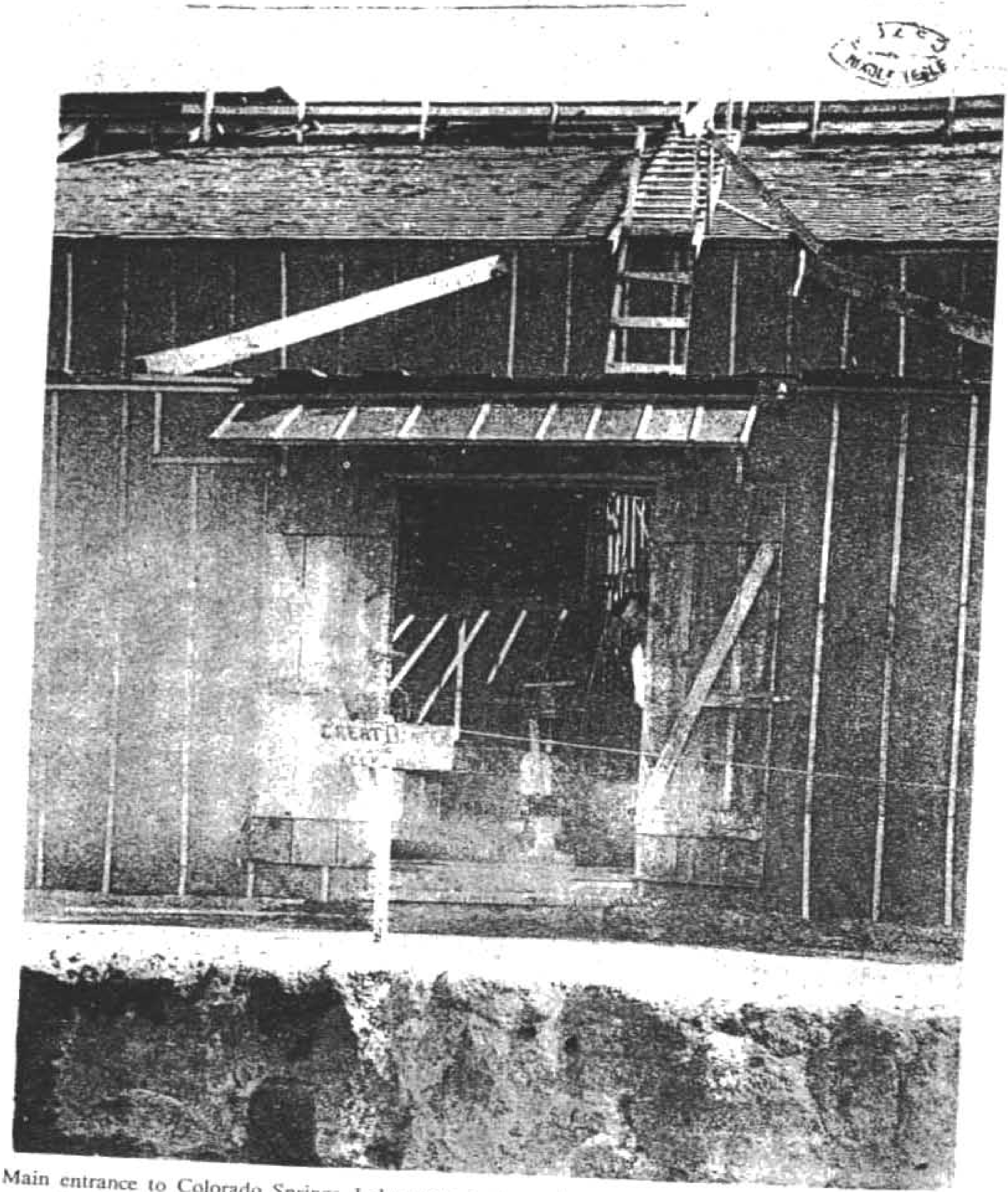
Measurements of the pole capacity, like those of November 7th, but now using a coil with 1314 turns. Resonance was determined by means of a small lamp in series with a coil loosely coupled to the measuring circuit. The value obtained was again similar, so Tesla concludes that it is near the true value of the effective capacity.

13 *November*

Tesla uses an improved method for determining the resonance point, with the light bulb in a dark box for more precise detection of luminance, and determines the capacity of the iron piping once more, obtaining a value about 10% less than in earlier measurements (see November 7th and 12th).

15 *November*

Tesla again measures the capacity of the sphere on top of the metal pole as on November 7th and 12th, but with the secondary coil of the oscillator instead of the earlier "supplementary" coils. The results did not agree with those obtained earlier. Tesla puts this down to the large distributed capacity of this coil, but it would seem that other factors influenced the accuracy as well. Because of the tight coupling between the primary and secondary of the oscillator, it was probably producing a compound spectrum.



Main entrance to Colorado Springs Laboratory in the early phase of development. Tesla is looking through the door (Tesla's own photograph now at the Nikola Tesla Museum, Belgrade)

16—20 *November*

Capacity measurements made during the period 16—22 November agree on the whole with those made earlier. Tesla does not explain why he repeated similar measurements, e.g. those of November 16th and 18th when he determined the distributed capacity of the supplementary coil and the vertical wire. Nor does he explain why he repeated the measurements of the change of capacity of the sphere with elevation (see November 18th and 20th). He may only have wanted to confirm the earlier results.

On November 17th and 19th he measured the capacity of a vertical wire of various lengths and gauges. From his comments on November 17th it may be seen that at greater h/λ klein! lengths he expected some inductive effect. A check of the wavelength, however, reveals that all Tesla's antennas were short in comparison (h/λ of the order of 0.01), so that divergence between the theoretical and measured values cannot be ascribed to an inductive effect.

21 *November*

For some reason which he does not explain, Tesla was interested in the capacity of the same wire when vertical and horizontal, which he measured by the usual resonance method, repeating it with a different capacitance in the primary as a check. Although the results from the two sets of measurements differ appreciably, the value obtained with the wire horizontal was somewhat higher in both cases. The formulae which Tesla used July 24th here yields 54.37 cm for the vertical wire and 58.43 cm for the horizontal. These values agree well with his measurements, especially the first set.

24—26 *November*

To check the values for the inductance in the primary circuit (of the oscillator) which he had earlier measured by the voltage, current and frequency method (see October 30th), Tesla repeats these measurements using the resonance method. He described the procedure on October 21st and made some measurements but did not follow them up with calculations. This time he made both measurements and calculations, but only for one L_pC_p combination. He compares them with values derived from the table given November 8th using linear interpolation. He was probably satisfied with the agreement, and did not make further checks. He had measured the capacity of the same structure, but without the protective cap and using the "extra" and "experimental" coils, on November 7th. On November 12th he had made similar measurements using the 1314-turn coil. In the 26 November entry he refers to the result of 7 November with a new "extra" coil. There is also one more result obtained with an "extra coil", using the best method he had developed for detecting resonance (see 13 November). This result, which differs appreciably from the others, is not mentioned November 26th.

The remark closing this entry suggests the possibility of a systematic error in the determination of resonance, and Tesla emphasizes that it has to be checked.

5 *December*

In this, as in earlier measurements, he found a "reduced inductance of the primary because of the reaction of the secondary". This interpretation of the functioning of the oscillator diverges from Oberbeck's theory[29]. If the spark duration is relatively long the oscillator starts to produce oscillations of two frequencies, and when the spark is broken it gives a third frequency which is determined by the secondary oscillatory circuit. With a third circuit ("extra coil") the oscillation of the system becomes even more complicated, the oscillations during break being determined by the secondary circuit and the "extra coil". Neglecting for the moment the "extra coil", the three frequencies which a Tesla oscillator with tight inductive coupling[31] and equal natural resonant frequencies of the coupled circuits can be expected to produce are

$$\omega_0 = \frac{1}{\sqrt{LC}} \qquad \omega_1 = \frac{1}{\sqrt{LC(1-k)}} \qquad \omega_2 = \frac{1}{\sqrt{LC(1+k)}}$$

where k is the coupling coefficient. Thus ω_1 can be interpreted as the natural frequency of a circuit with capacity C and inductance $L\,(1-k)$. For the primary inductance of Tesla's oscillator (see 9 November) one obtains the "reduced" L, i.e. $L\,(1-k)=23{,}094$ cm; Tesla measured $L=24{,}063$ cm.

6 *December*

The photographs of the inside of the laboratory show the 100-turn "extra coil" raised above the floor in the center. With this coil Tesla again got similar results for the "reduced" inductance of the primary. However, aware of the indeterminacy of this "reduction", and hence also of the oscillation frequency, he notes that the secondary should be broken at more points when the primary is used as a measuring inductance. This would ensure monochromatic oscillation of the oscillator by reducing the coupling of the primary and secondary (i.e. the circuit of the "extra coil"). The measurements with the secondary eliminated are more reliable, and the accuracy with which the values sought are determined depends mainly on the accuracy to which the inductance and capacitance in the exciting circuit of the oscillator are known.

1 *January*

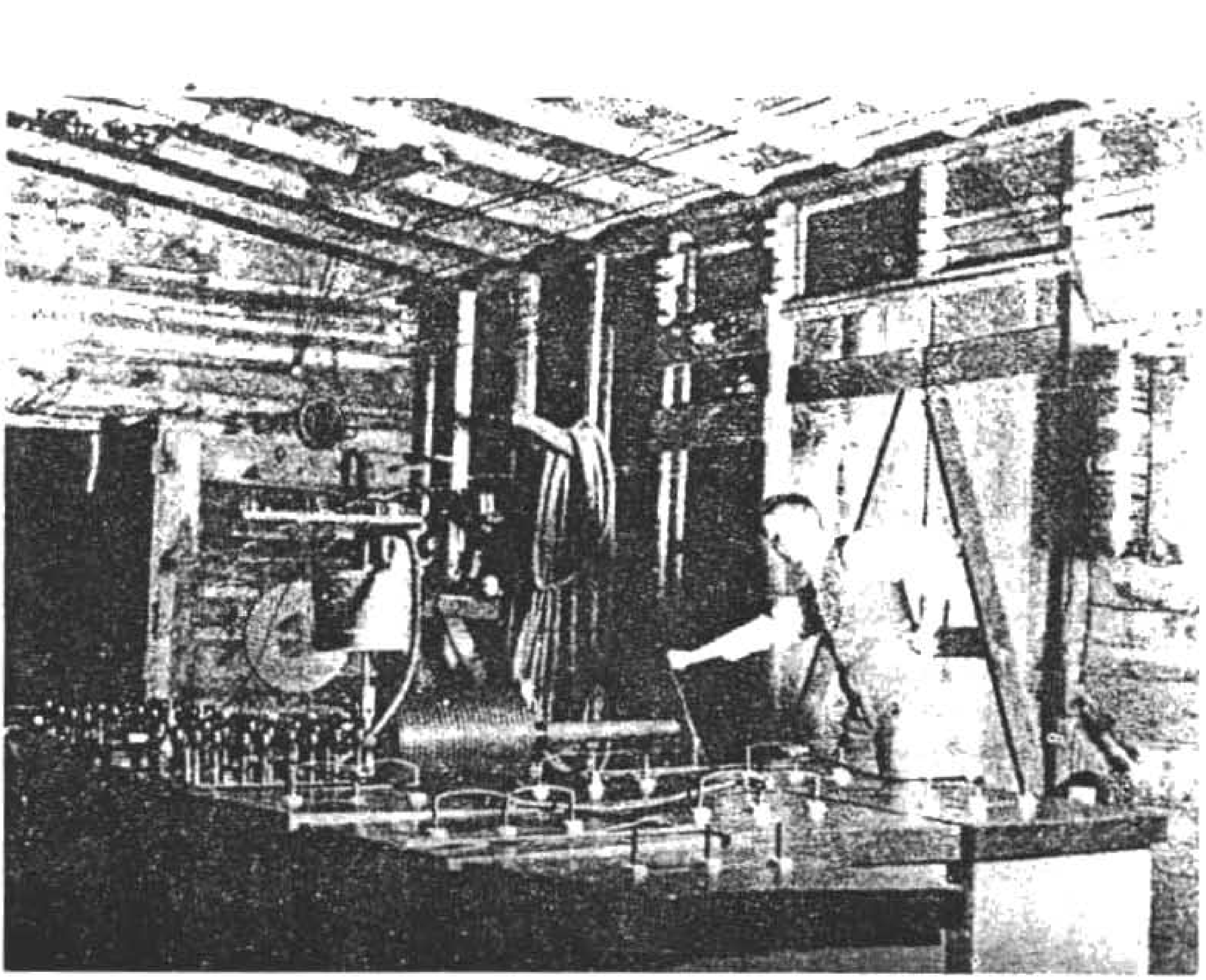
Photograph XVII shows lamps connected into a resonant circuit consisting of one square turn. According to the data Tesla gives, one side of the square was about 1.3 m from the secondary coil of the oscillator. The capacity of the oscillatory circuit consisted of two condensers in parallel. The lamps are paralleled.

Tesla calculates the inductance of the square turn from the formula for the inductance of two parallel conductors, as if there were two such pairs connected in series. The formula for a square coil (Fleming, p. 155),

$$L = 8\,l\left(\ln\frac{d}{r} - 0.774\right)$$

yields a value 12.6% less than Tesla found. The calculated resonant frequency is therefore somewhat higher than it should be, so that the inductance of the oscillator primary, as Tesla calculates it, is still less. In fact, because of the tight coupling of the secondary the oscillator must have been producing a complex spectrum, probably with its strongest component at the resonant frequency of the oscillatory circuit of the square coil.

In connection with photographs XVIII—XXI showing the secondary producing intense discharges, Tesla makes an interesting remark about signalling over great distances. Comparing this with other induction apparatuses he had constructed, he concludes that



Interior of Colorado Springs Laboratory

one could expect signals to be picked up at distances of a thousand miles or more, even on the Earth's surface. The diary does not mention any measurements at great distances, but in an article[41] he published soon after finishing work at Colorado Springs he states that he observed effects at a distance of about 600 miles.

2 *January*

In this entry of 21 pages (the longest in the Notes) Tesla describes 11 photographs.

The explanation to Photograph XXII concerning the transmission of power from the excited primary circuit to the "extra coil" via the earth is similar to that he gave in 1893[6]. The experiment to which the photograph refers was made with the aim of estimating the power of the oscillator from the thermal effect of the HF current. What Tesla calls the "total energy set in movement" would correspond to the total energy transferred to condenser in the secondary (i.e. the power) if an energy of $\frac{1}{2}CV^2$ is transferred in each half-cycle. It can be shown that the active power dissipated in the circuit is much less than this and is inversely proportional to the Q-factor of the oscillating circuit.

The next few photographs show a movable coil which powers light bulbs by means of the high-frequency power which it picks up. One end of the coil is grounded, the other free or just connected to a short piece of wire. The bulbs are inductively coupled to the resonant coil via the auxiliary secondary. Tesla gives no data about the distance of the resonant coil from the oscillator coil.

Tesla's commentary on photograph XXVIII illustrates that he still retained a lively interest in the problem of electric lighting, even after a period of over ten years. His earlier discovery of the luminescence of the gas and not only the filament with HF currents was here again confirmed[5].

In photograph XXVIII the bulb is connected in series with the terminal capacitive load. In the calculation Tesla does not use the "total energy set in movement" but assumes that $\frac{1}{2}CV^2$ of electrostatic energy is consumed in the bulb in each half-cycle. A similar comment applies to photograph XXIV.

Several times Tesla remarks that the principle energy transfer from the oscillating to the receiving coil takes place via the earth. He finds confirmation for this in the experiment described on p. 363 (photograph XXX). He found that the voltage induced in the receiving coil was greatly reduced if the ground connection was broken. It may be that such experiments led him to the conclusion that "transmission" through the earth was a more efficient method of wireless transmission of power than the "inductive method".

Photograph XXXI is an X-ray picture of a finger. Tesla's comments on this experiment illustrate his interest in this type of radiation, already referred to (see the commentary to 6 June 1899).

3 *January*

After describing some photographs of the laboratory, in the commentary to photograph XLI Tesla explains some transformations of the streamers. He mentions the splitting of streamers near the floor, splitting and reuniting, the phenomenon of luminous parts on the streamers (which he then refers to as sparks), and the breaking up of sparks into streamers and fireballs. His remarks concerning the genesis of fireballs are particularly noteworthy. This phenomenon has been a source of interest since ancient times. Some references to it can be found on Etrurian monuments, in the works of Aristotle, Lucretius and other old sources[63]. Fireballs are considered to be a form of electrical discharge generated during thunderstorms. They are rare in nature, but a fair-sized body of observations has nevertheless been assembled upon which several theories of their origin have been founded. Some hypotheses maintain that fireballs are an optical illusion (an opinion shared by Tesla until he produced them himself), others that they are the traces of meteors. The first genuine scientific approach to the problem was Arago's analysis of some twenty reports of fireballs in 1838. After the publication of his work they became a legitimate subject of scientific interest, but to this day have remained something of an enigma.

A fireball is a luminous sphere occurring during a thunderstorm. Fireballs are usually red, but other colors have also been observed: yellow, green, white and blue. Their dimensions vary, a mean diameter being about 25 cm. Unlike ordinary lightning, fireballs move slowly, almost parallel to the ground. They sometimes stop and change their direction of motion. They can last for up to 5 seconds. Their properties vary greatly from case to case, so that it is believed that there are various types. According to Singer[63] it can be stated that as yet no single theory can explain the occurrence of fireballs in nature.

Despite numerous attempts, only a few types of fireball have been created, and not entirely successfully, in the laboratory. These include the weakly luminescent fireballs generated when ordinary lightning strikes some object. Tesla mentions phenomena of this type several times as the result of sparks or streamers striking wooden objects (see e.g. photograph XL). According to recent theories, fireballs consist of a plasma zone created by electrical discharge. The latest research and calculations by Kapitsa[64] show that the lifetime of a fireball cannot be explained by the energy it receives at the time of genesis, but that it must receive energy from its surroundings. Kapitsa theorizes that this external energy is produced by a naturally created electromagnetic field. The small zone of ionized gas created by the initial lightning or other electrical phenomenon during the storm subsequently expands at the expense of the external electromagnetic field. The diameter of the plasma sphere is determined by the frequency of the external field, so that a resonance occurs. The usual dimensions of fireballs would require that the electromagnetic field have a wavelength of between 35 and 100 cm. According to this theory standing waves created by the reflection of natural electromagnetic waves from the earth would play a certain role. The theory has obtained partial experimental confirmation, but there are still many points on which it is unable to give a satisfactory explanation. It has been found that to maintain a lump of plasma in air requires a power of the electromagnetic field of about 500 W, which is much less than power which can be produced by an electrical discharge. However, too little is known about natural electromagnetic waves to allow any reliable conclusions to be drawn.

Tesla's hypothesis on the origin and maintenance of fireballs includes some points which are also to be found in the most recent theories, but it also bears the stamp of the time. For instance, like Kapitsa, Tesla considers that the initial energy of the nucleus is not sufficient to maintain the fireball, but that there must be an external source of energy. According to Tesla this energy comes from other lightnings passing through the nucleus, and the concentration of energy occurs because of the resistance of the nucleus, i.e. the greater energy-absorbing capacity of the rarefied gas than the surrounding gas through which the discharge passes. In nature the probability of other discharges passing through the nucleus of a fireball is small, so Kapitsa's hypothesis that act via electromagnetic standing waves is more logical. It is possible that in Tesla's experiments the "passage" of a number of later discharges through the same nucleus was more frequent.

7 January

This is the last entry in the diary. Apart from the usual description of photographs, Tesla writes about experiments he intends to carry out on his return (where?). He qualifies the experiments to date as satisfactory, considering that his aim was "to perfect the apparatus and make general observations". The apparatus which he was then envisaging for future experiments was to be an improved oscillator which would enable better results than any he had so far obtained.

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