April 20, 1893.

The LORD KELVIN, D.C.L., LL.D., President, in the Chair.

A List of the Presents received was laid on the table, and thanks ordered for them.

The following Papers were read :—

I. "Magnetic Viscosity." By J. HOPKINSON, D.Sc., F.R.S., E. WILSON, and F. LYDALL. Received March 8, 1893.

The following experiments were carried out in the Siemens Laboratory, King's College, London, and are a continuation of experiments by J. Hopkinson and B. Hopkinson, a description of which appeared in the 'Electrician,' September 9, 1892.

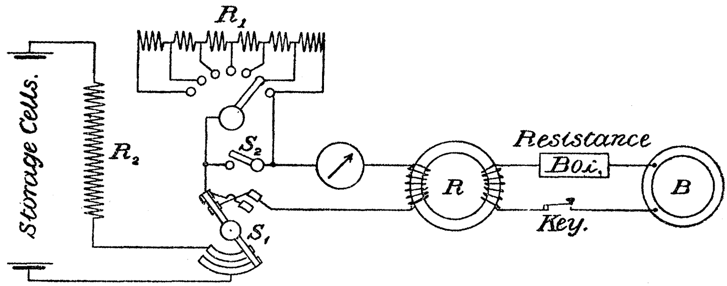
In that paper determinations were given of curves showing the relation between the induction and the magnetising force, for rings of fine wire of soft iron and steel, through complete cycles with varying amplitudes of magnetising force, both with the ordinary ballistic method and with alternating currents of a frequency up to 125 complete periods per second. It was shown that if the induction was moderate in amount, for example, 3000 or 4000, the two curves closely agreed; but, if the induction was considerable, for example, 16,000, the curves differed somewhat, particularly in that part of the curve preceding the maximum induction. The difference was greater with steel than with soft iron.

It was not then determined whether this difference was a true time effect or was in some way due to the ballistic galvanometer. The present paper is addressed to settling this point.

The ring to which the following experiments refer is of hard steel containing about 0·6 per cent. of carbon, in the form of wire $\frac{1}{100}$ in. diameter, varnished with shellac to ensure insulation. The material was supplied by Messrs. Richard Johnson. The ring is about 9 cm. diameter, and has a sectional area of 1·08 sq. cm.; it is wound with 200 turns of copper wire, and with 80 turns of fine wire for use with the ballistic galvanometer.

In the 'Electrician' paper the static curve of hysteresis was determined by the ballistic galvanometer, the connexions being made according to the diagram in fig. 1: where R is the hard steel wire ring, B is the ballistic galvanometer, S_1 is a reversing switch, and S_2 is a small short-circuiting switch for the purpose of suddenly insert-

FIG. 1.



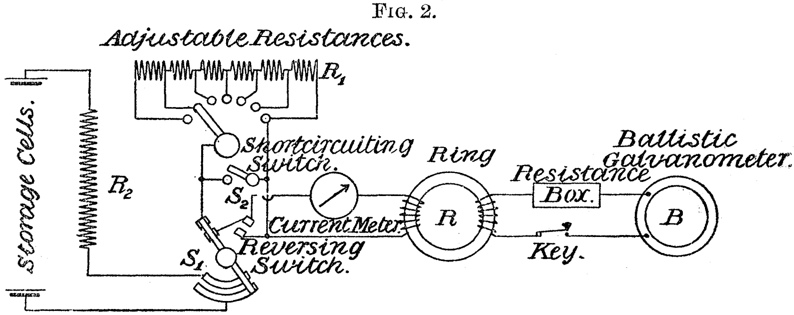
ing a resistance R_1 into the primary circuit. The resistance R_2 was so adjusted that the maximum current in the primary circuit was such as to give the desired maximum magnetising force on the ring.

In taking the kicks on the ballistic galvanometer the method adopted was as follows :—Having closed the primary by means of S_1, the switch S_2 was suddenly opened, thus allowing the magnetising force to drop to an amount determined by R_1, and the kick observed. A total reversal was then taken with S_1, and the kick again observed. The closing of S_2 again brought up the magnetising force to its maximum in the opposite direction to that at starting.

In a letter to the editor of the 'Electrician,' September 16, 1892, Mr. Evershed stated that "Had the slow cycle been obtained by the method described by Mr. Vignoles,* Messrs. Hopkinson would have found it in almost absolute agreement with the quick cycle curve."

To settle this point the static curve of hysteresis was obtained by the ballistic galvanometer, the connexions being made according to the diagram in fig. 2. This is not the method of experiment alluded

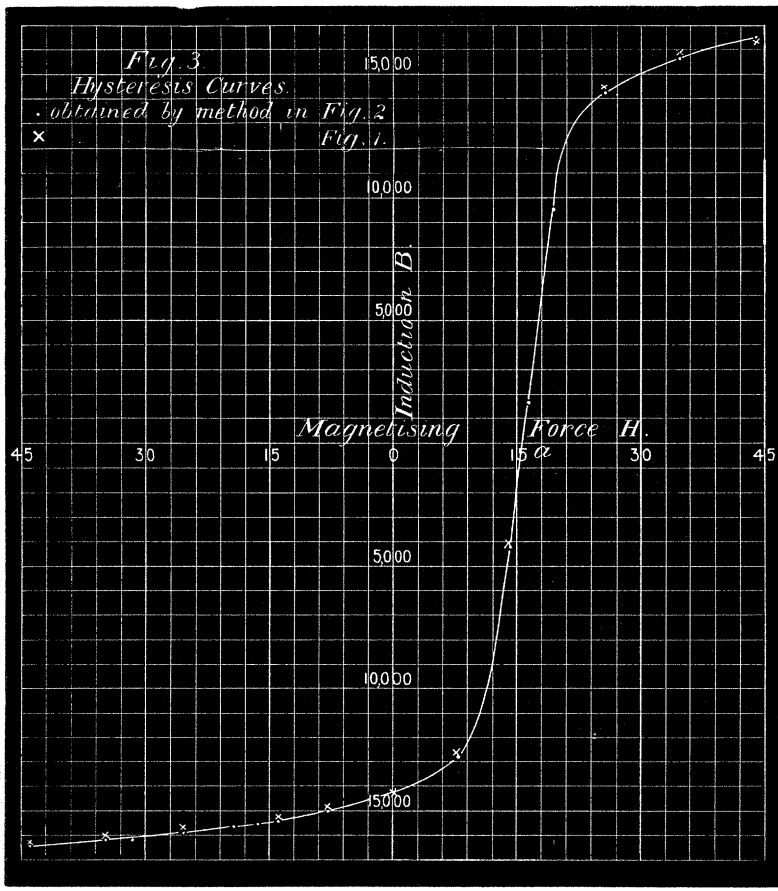
FIG. 2.



to by Mr. Evershed, but it is capable of varying the magnetising force in the same way as is described by him. R is the hard steel

* 'Electrician,' May 15 and 22, 1891.

wire ring, B is the ballistic galvanometer, S_1 is a reversing switch, and S_2 a small switch for the purpose of short-circuiting the adjustable resistance R_1. The difference between this diagram and that in fig. 1 is that R_1 can be suddenly inserted into the primary circuit by one stroke of the reversing switch S_1. In this way it is possible to vary the magnetising force from one maximum through zero to any desired point within the other maximum by one motion of the switch S_1: which operation takes but a small fraction of a second to perform.



In fig. 3 the points marked × were obtained by the method in fig. 1; the points marked · being obtained by the method in fig. 2. Table I gives the values for B and H, from which these points have

been plotted, and their close agreement proves that the difference found between the static and quick cycle curves is not due to the cause suggested by Mr. Evershed. In each case the battery used had a potential difference of 108 volts, the periodic time of the ballistic needle being 10 seconds.

It was observed, when taking the hysteresis curve by the method in fig. 2, that the sum of the inductions found by varying the magnetising force from one maximum to an intermediate point, and from that point to the other maximum, did not exactly equal the induction got by varying the magnetising force direct from one maximum to the other.

To investigate this with the ballistic galvanometer the magnetising force (fig. 3) was taken from one maximum through zero to the point *a* by one motion of the reversing switch handle, and the galvanometer circuit closed at known intervals of time *after* such change, the deflection being noted. This deflection does not represent an impulsive electromotive force, nor yet a constant current, but is caused by a current through the galvanometer diminishing in amount somewhat rapidly. It might arise from the comparatively slow rate at which the magnetising current changes, owing to the self-induction of the circuit, or it might arise from a finite time required to develop the induction corresponding to a given magnetising force. The former would be readily calculable if the ring had a definite self-induction; in our case it is approximately calculable.

Let R be resistance of primary circuit, E the applied electromotive force, x the current, and I the total induction multiplied by the number of primary turns.

$$E = Rx + \frac{dI}{dt}.$$

Now I is known in terms of x for conditions of experiment very approximately, and roughly dI/dt has a constant ratio to dx/dt—is equal, say, to $L(dx/dt)$; hence the well known equation

$$E = Rx + L\frac{dx}{dt},$$

$$x = \frac{E}{R}\left(1 - \epsilon^{-\frac{R}{L}t}\right).$$

From our curves we see that induction per sq. cm. increases 10,000, whilst magnetising force increases 4. Total induction multiplied by the primary turns, taking the volt as our unit, increases $10{,}800 \times 200 \times 10^{-8}$, whilst the current increases $\frac{1}{2}$ an ampère, *i.e.*,

$$L = 4{\cdot}32 \times 10^{-2}.$$

In the experiments made E = 4 and 108 volts and R = 0·8 and 21·6 ohms, whence

$$x = 5\left(1-\epsilon^{-\frac{80}{4\cdot32}t}\right) \text{ and } 5\left(1-\epsilon^{-\frac{2160}{4\cdot32}t}\right).$$

In either case x does not differ sensibly from its final value when $t = \frac{2}{5}$ second. Hence the self-induction of the circuit can have nothing to do with the residual effects observed.

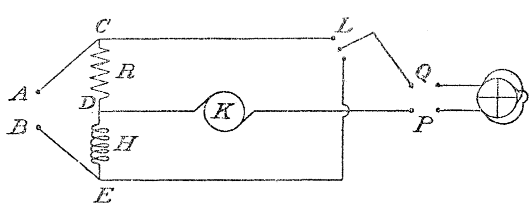
These experiments showed that an effect was produced upon the galvanometer needle, appreciable for some seconds, the effect being somewhat more marked with 4 than with 108 volts. But the whole amount was so small as to be less than 1 per cent. of the total change of induction; from which we infer that no material difference exists between curves of induction determined by the ballistic galvanometer and the inductions caused by magnetising forces operating for many seconds.

Effect of tapping the Specimen.—Having taken the magnetising force from its maximum through zero to the point a as before, the effect of tapping was marked, especially in the case of soft iron, when a kick corresponding to an acquirement of 633 lines of induction per sq. cm. was observed.

The following experiments on the hard steel wire ring were carried out with the alternator, the object being to ascertain if a time effect on magnetism exists. The ballistic curve (fig. 3) has been taken as a standard with which to compare the respective hysteresis curves. In each case the maximum magnetising force has been made as nearly as possible to agree with that used when taking the ballistic curve, and the method of test was that employed in the 'Electrician' paper. For the sake of completeness the diagram, fig. 4, and description are given over again.

Quoting from that paper, we have: "For determining the points on the closed curve of magnetisation given by rapid reversals of the current in the coil, the ring was connected in series with a non-inductive resistance to the poles of an alternate current generator, or a transformer excited by the generator, thus :—

FIG. 4.



in which A, B are the poles of the transformer or generator; C, D the terminals of the non-inductive resistance R; H the coil surrounding the ring; P and Q the studs of a reversing key connected to the quadrant of a Thomson quadrant electrometer; L a key by means of which Q could be connected with C or E at will; and K a revolving contact maker, through which P was connected to D. A condenser was connected to P and Q, in order to steady the electrometer readings. The contact maker K was bolted on to the axle of the generator. It consists of a circular disc of ebonite, about 13 in. in diameter, having a small slip of copper, about $\frac{1}{16}$ in. wide, let into its circumference. A small steel brush presses on the circumference, and makes contact with the piece of copper once in every revolution. The position of the brush can be read off on a graduated circle. The quadrant electrometer thus gives the instantaneous value of the difference of potential between the points C and D, or the points D and E, according to the direction of the key L."

Frequencies of 5, 72, and 125 ~ per second have been tried, two values being given to the potential difference at the terminals of the alternator in each of the frequencies 72 and 125, making in all 5 complete experiments. The curves so obtained are given in figs. 8, 9, 10, 11, and 12 respectively. From observations of the values of the electromotive force between C and D (fig. 4) at different times in the period, a curve A (in each experiment) was plotted, giving the magnetising force in terms of the time; a similar curve was plotted for the electromotive force between D and E, which, when corrected by subtracting the electromotive force due to the resistance of the coil H, gives the potential or time rate of variation of the induction in terms of the time. Hence the area of this curve (B) up to any point, *plus* a constant, is proportional to the induction corresponding to that point. This is shown in curve C, which is the integral of B. In each of the five experiments the ring with the non-inductive resistance was placed across the terminals of the alternator, and the excess of potential taken up by a non-inductive resistance.

In fig. 5 the hysteresis curves for frequencies of 5, 72, and 125 are compared with the ballistic curve. These curves are marked 5, 72L, and 125L respectively. The corresponding values for B and H, from which these curves have been plotted, are given in Tables II, III, V, which have been obtained from the curves in figs. 8, 9, and 11 respectively.

The most noteworthy features in these curves are that the curve with a frequency of 5 is very near the ballistic curve, if allowance is made for difference in the magnetising current, and that the curves with a frequency of 72 and 125 deviate very materially, particularly in the part of the curve somewhat preceding the maximum induction. Hence the time effect mainly develops with a greater frequency than

5 per second. Hence also we infer that this effect, as already described in the 'Electrician,' is a true time effect, not arising in any way from the ballistic galvanometer.

In fig. 6 the hysteresis curves for a frequency of 72 are compared with the ballistic curve. The curves are marked 72L and 72H respectively, the potentials at the terminals of the alternator in the two cases being approximately 36 and 430 volts. The corresponding values for B and H are given in Tables III, IV, which have been obtained from the curves in figs. 9 and 10 respectively.

The difference between the two curves in fig. 6 was at first puzzling, but a little consideration satisfied us that it arises from the same time effect. The curve 72L was determined three times, with the same result. The numerals refer to thirtieths of a half-period. From 26 to 28·8 of the L curve the magnetising force increases from 31·8 to 45·6, whilst from 21 to 26 of the H curve it increases from 30·6 to 44, the rate of change being about double as great in the former case as in the latter, and it is the L curve which deviates most from the ballistic curve. In like manner, in the neighbourhood of zero induction, the induction in the H curve is changing twice as fast as the induction of the L curve, and it is here the H curve which differs most. How these differences of rate of change arise can be seen by inspecting figs. 9 and 10.

In fig. 7 the hysteresis curves for a frequency of 125 are compared with the ballistic curve. The curves are marked 125L and 125H respectively, the potentials at the terminals of the alternator being approximately 62 and 750 volts. The corresponding values for B and H are given in Tables V and VI, which have been obtained from the curves in figs. 11 and 12 respectively.

These curves show the same difference as fig. 6, but less markedly than in fig. 5. The L curve was determined twice.

Experiments have been made upon chromium steel, supplied by Mr. Hadfield, having the following composition:—0·71 per cent. carbon, 9·18 per cent. chromium, when annealed, and when hardened by raising to low yellow and plunging into cold water. The results show that the same time effect exists in this case, although it was not so marked as in the case of the hard steel.

We draw the following conclusions from these experiments:—(1.) As Professor Ewing has already observed, after sudden change of magnetising force, the induction does not at once attain to its full value, but there is a slight increase going on for some seconds. (2.) The small difference between the ballistic curve of magnetisation with complete cycles and the curve determined with a considerable frequency, which has already been observed, is a true time effect, the difference being greater between a frequency of 72 per second and 5 per second than between 5 per second and the ballistic curve.

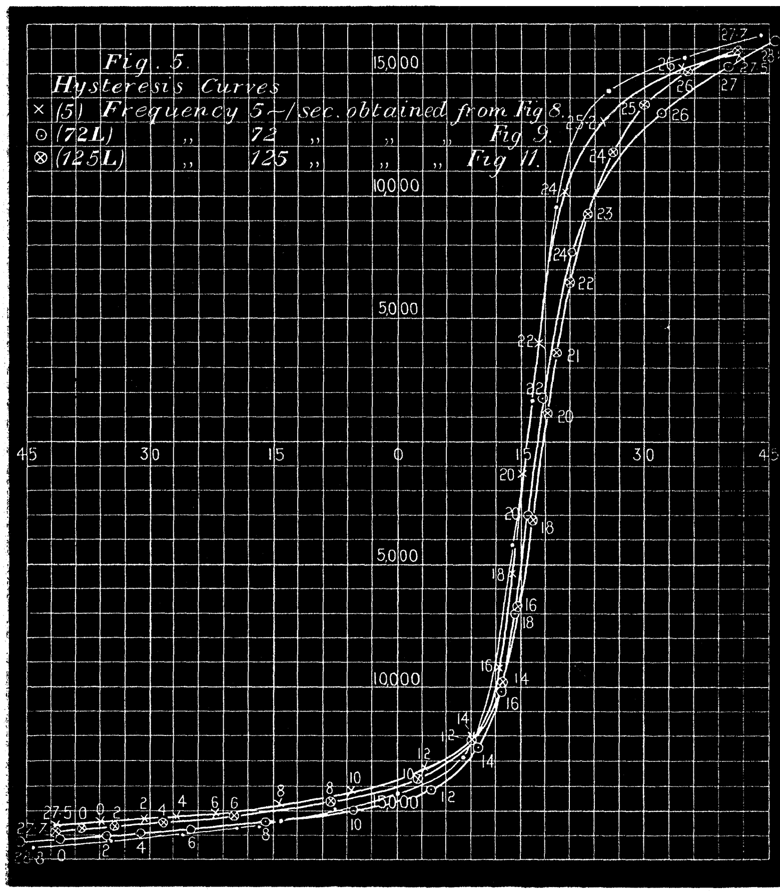


Fig. 5.
Hysteresis Curves
× (5) Frequency 5 ~/sec. obtained from Fig 8.
⊙ (72L) ,, 72 ,, ,, ,, Fig 9.
⊗ (125L) ,, 125 ,, ,, ,, Fig 11.
15,000
10,000
5,000
45
30
15
0
15
30
45
5,000
10,000
15,000

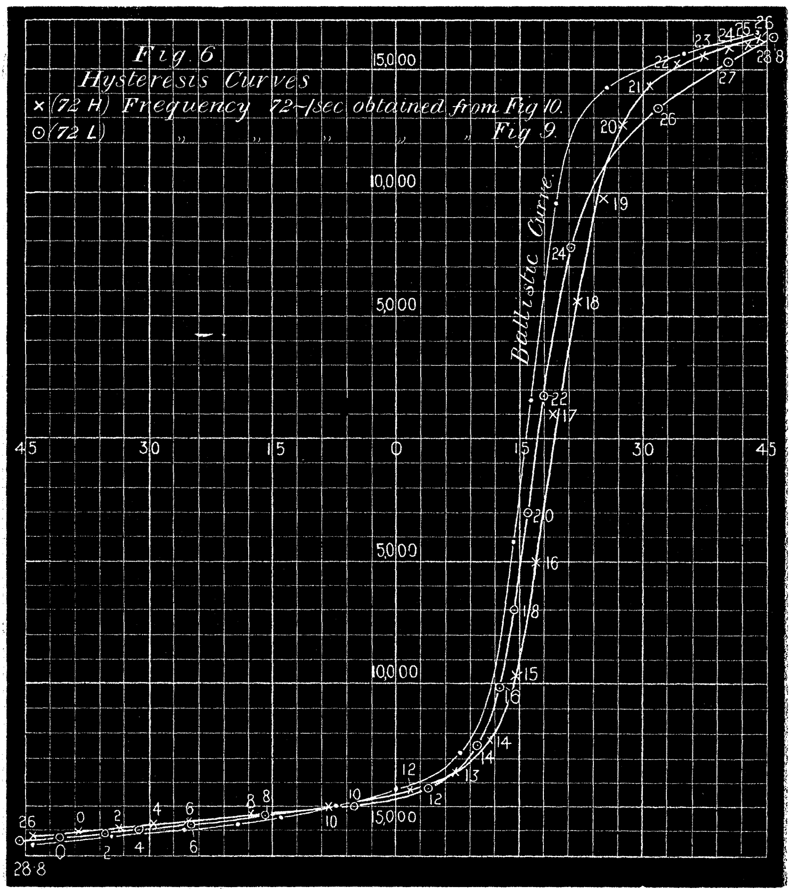


Fig. 6.
Hysteresis Curves
× (72 H) Frequency 72~/sec obtained from Fig 10.
⊙ (72 L) " " " " " Fig 9.
Ballistic Curve.
15,000
10,000
5,000
45
30
15
0
15
30
45
5,000
10,000
15,000
28·8

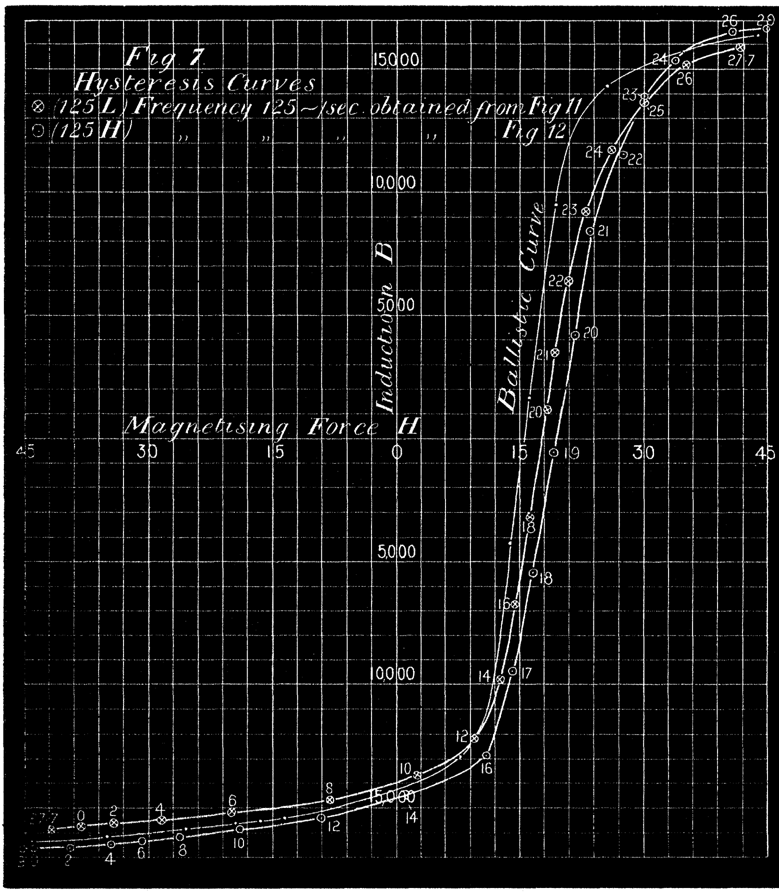


Fig 7.
Hysteresis Curves
⊗ (125 L) Frequency 125~/sec. obtained from Fig 11
⊙ (125 H) ,, ,, ,, ,, Fig 12
Induction B
Magnetising Force H
Ballistic Curve
15000
10000
5000
0
15
30
45

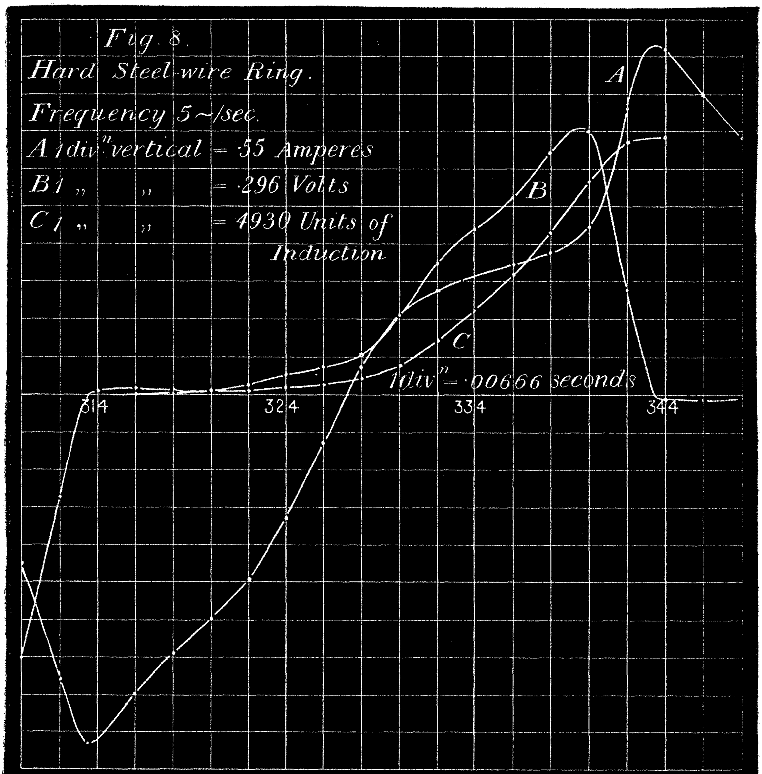


Fig. 8.
Hard Steel-wire Ring.
Frequency 5 ~/sec.
A 1 div" vertical = ·55 Amperes
B 1 " " = ·296 Volts
C 1 " " = 4930 Units of Induction
A
B
C
1 div" = ·00666 seconds
314
324
334
344

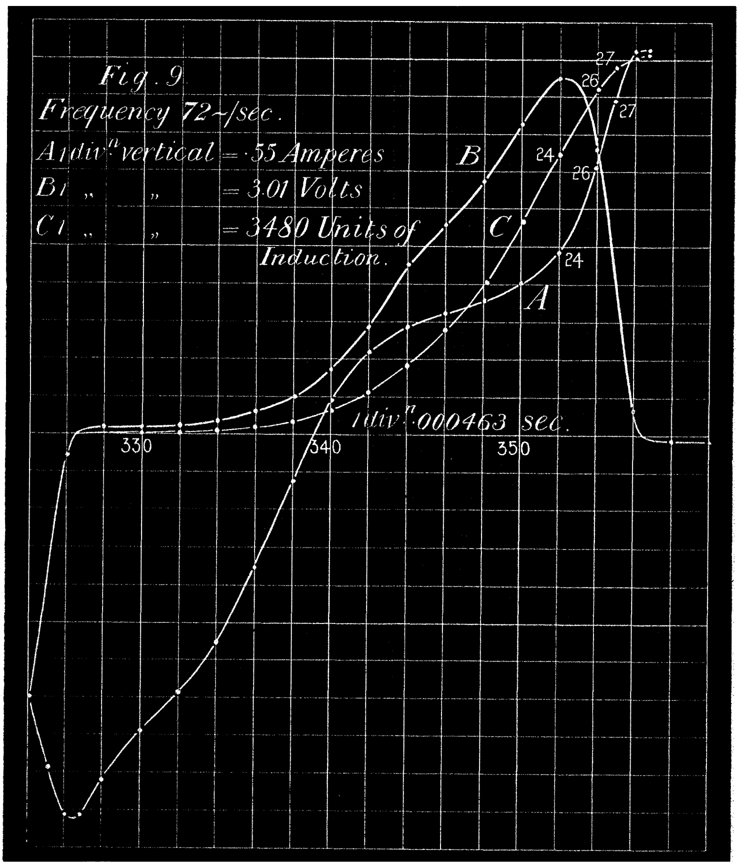


Fig. 9.
Frequency 72~/sec.
A 1 div.n vertical = ·55 Amperes
B 1 „ „ = 3.01 Volts
C 1 „ „ = 3480 Units of Induction.
1 div.n ·000463 sec.
330
340
350
A
B
C
24
26
27

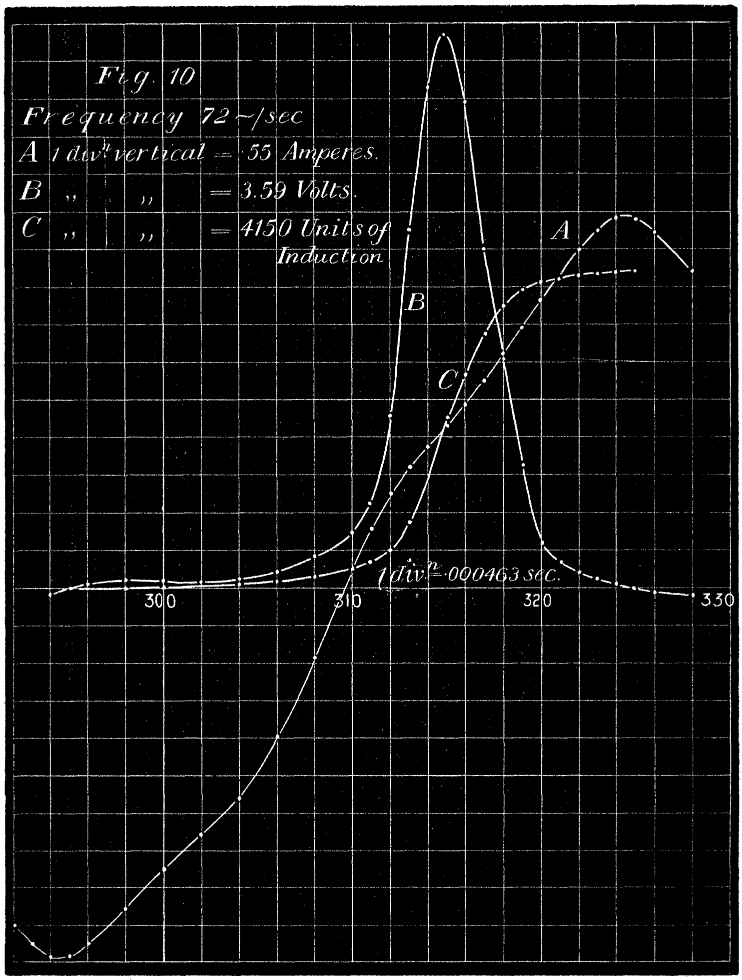


Fig. 10
Frequency 72 ~/sec
A 1 divn vertical = ·55 Amperes.
B ,, ,, = 3.59 Volts.
C ,, ,, = 4150 Units of Induction
A
B
C
1 divn = ·000463 sec.
300
310
320
330

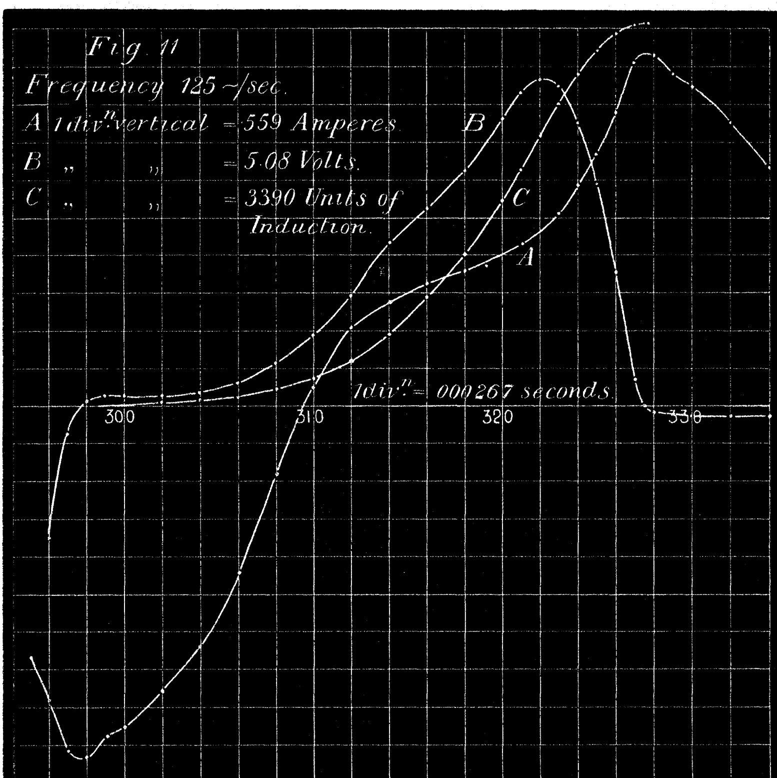


Fig. 11
Frequency 125 ~/sec.
A 1 divn. vertical = 559 Amperes.
B " " = 5·08 Volts.
C " " = 3390 Units of Induction.
B
C
A
1 divn. = ·000267 seconds.
300
310
320
330

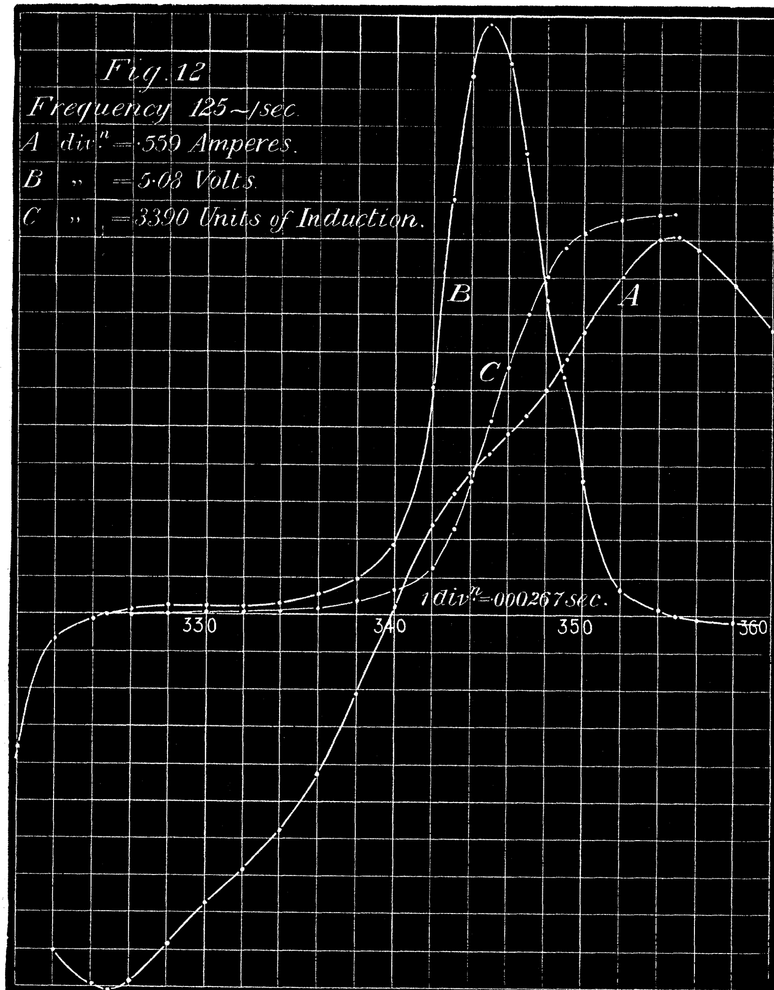


Fig. 12
Frequency 125~/sec.
A div.n = ·559 Amperes.
B " = 5·08 Volts.
C " = 3390 Units of Induction.
B
C
A
1 divn = ·000267 sec.
330
340
350
360

Table I.—Hard Steel-wire Ring.

H.	B. Points marked × obtained by method shown in fig. 1.	B. Points marked • obtained by method shown in fig. 2.
+44·12	16,295	16,436
34·77	15,830	15,650
25·44	+14,407	14,290
19·32	..	9,539
16·1	..	+ 1,704
14·2	− 4,045	− 4,130
7·73	12,690	12,820
0	..	14,280
− 7·73	14,870	14,990
14·2	15,270	15,380
16·1	..	15,460
19·32	..	15,630
25·44	15,733	15,860
34·77	16,033	16,150
44·12	16,295	16,436

Table II.—Frequency 5 per second.

B.	H.
15,660	41·7
15,200	34·4
13,010	25·1
10,190	19·95
+ 3,970	17·1
− 1,230	15·3
5,340	14·1
9,176	12·3
12,007	9·4
13,377	+ 3·4
14,382	− 5·6
14,747	14·4
15,203	22·0
15,295	26·85
15,477	30·86
15,523	35·75
15,660	41·7

Table III.—Frequency, 72 per second. Potential at Terminals of Alternator, approximately 36 Volts.

B.	H.
16,245	+ 45 ·7
16,180	45 ·5
15,215	39 ·9
13,410	31 ·7
7,805	21 ·3
+ 1,805	17 ·8
− 3,030	15 ·8
7,027	14 ·3
10,121	12 ·6
12,506	9 ·86
14,118	4 ·26
14,956	− 5 ·44
15,407	15 ·86
15,729	24 ·77
15,923	31 ·1
16,116	35 ·4
16,219	40 ·9
16,245	45 ·7

Table IV.—Frequency, 72 per second. Potential at Terminals of Alternator, approximately 430 Volts.

B.	H.
16,221	43 ·98
16,214	44 ·32
16,069	42 ·75
15,919	40 ·61
15,685	37 ·25
15,299	34 ·33
14,299	30 ·97
12,689	27 ·6
9,839	24 ·91
5,539	21 ·88
+ 999	19 ·3
− 5,073	16 ·6
9,609	14 ·36
12,300	11 ·22
13,530	7 ·18
14,145	+ 2 ·24
14,991	− 8 ·08
15,452	17 ·72
15,644	25 ·13
15,814	29 ·62
15,914	33 ·66
16,122	38 ·37
16,221	43 ·98

Table V.—Frequency, 125 per second. Potential at Terminals of Alternator, approximately 62 Volts.

B.	H.
15,936	+ 41 ·74
15,746	40 ·95
15,119	35 ·00
13,739	30 ·07
11,732	26 ·48
9,222	23 ·11
6,462	20 ·87
3,576	19 ·19
+ 1,192	18 ·18
− 3,136	16 ·16
6,776	14 ·59
9,850	12 ·57
12,172	9 ·20
13,615	2 ·24
14,618	− 8 ·08
15,120	19 ·75
15,434	28 ·61
15,622	34 ·10
15,773	38 ·37
15,936	41 ·74

Table VI.—Frequency, 125 per second. Potential at Terminals of Alternator, approximately 750 Volts.

B.	H.
16,689	+ 45 ·1
16,671	44 ·65
16,565	40 ·72
15,311	33 ·66
13,930	30 ·18
11,544	27 ·15
8,411	23 ·78
+ 4,077	21 ·54
− 565	19 ·30
5,396	16 ·83
9,474	14 ·36
12,862	10 ·77
14,368	1 ·12
15,309	− 9 ·20
15,873	18 ·85
16,099	26 ·25
16,262	30 ·63
16,413	34 ·33
16,564	39 ·49
16,670	43 ·98
16,689	45 ·10

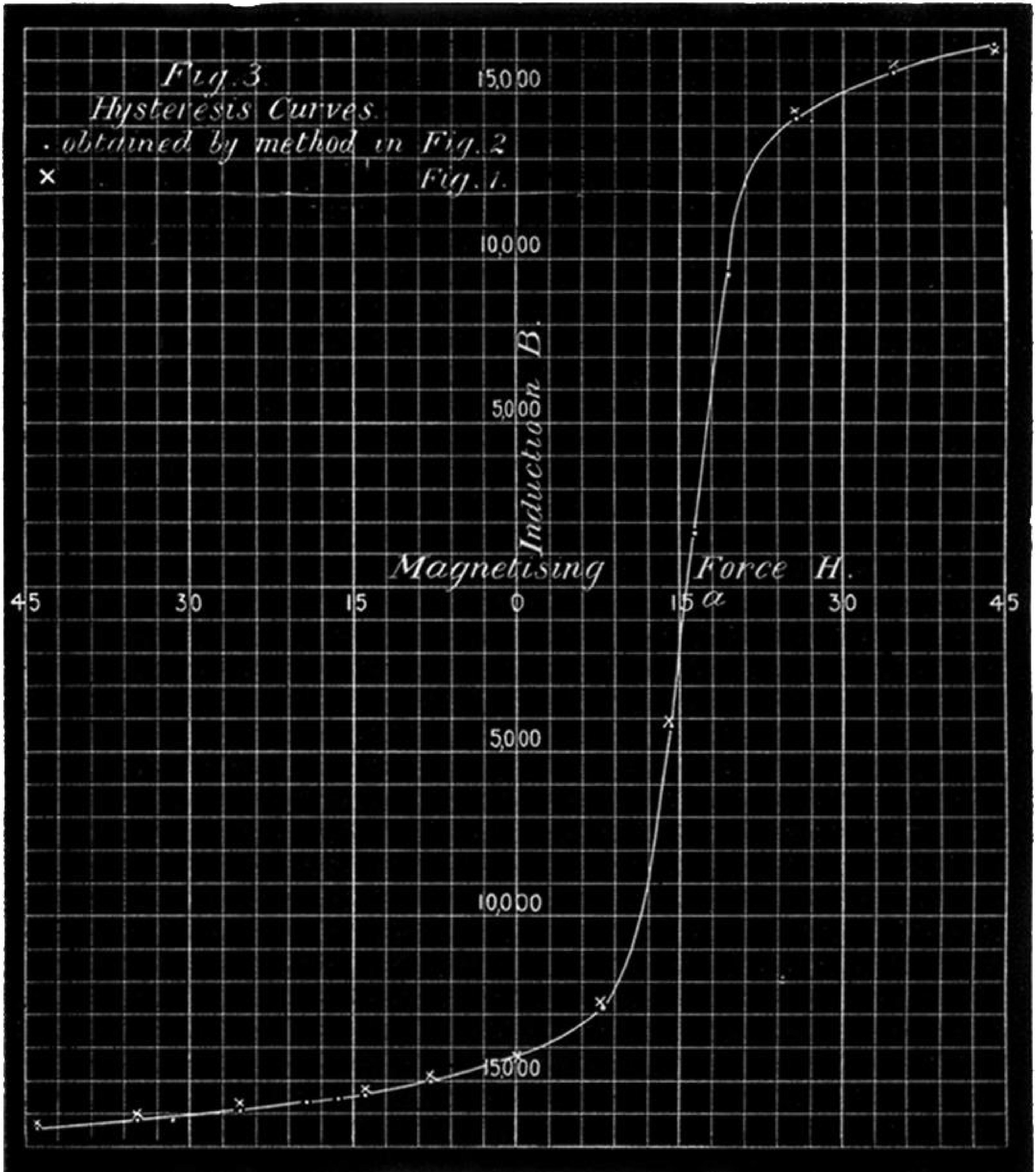


Fig. 3
Hysteresis Curves
. obtained by method in Fig. 2
× Fig. 1.
Induction B.
Magnetising Force H.
15,000
10,000
5,000
5,000
10,000
15,000
45
30
15
0
15
30
45
a

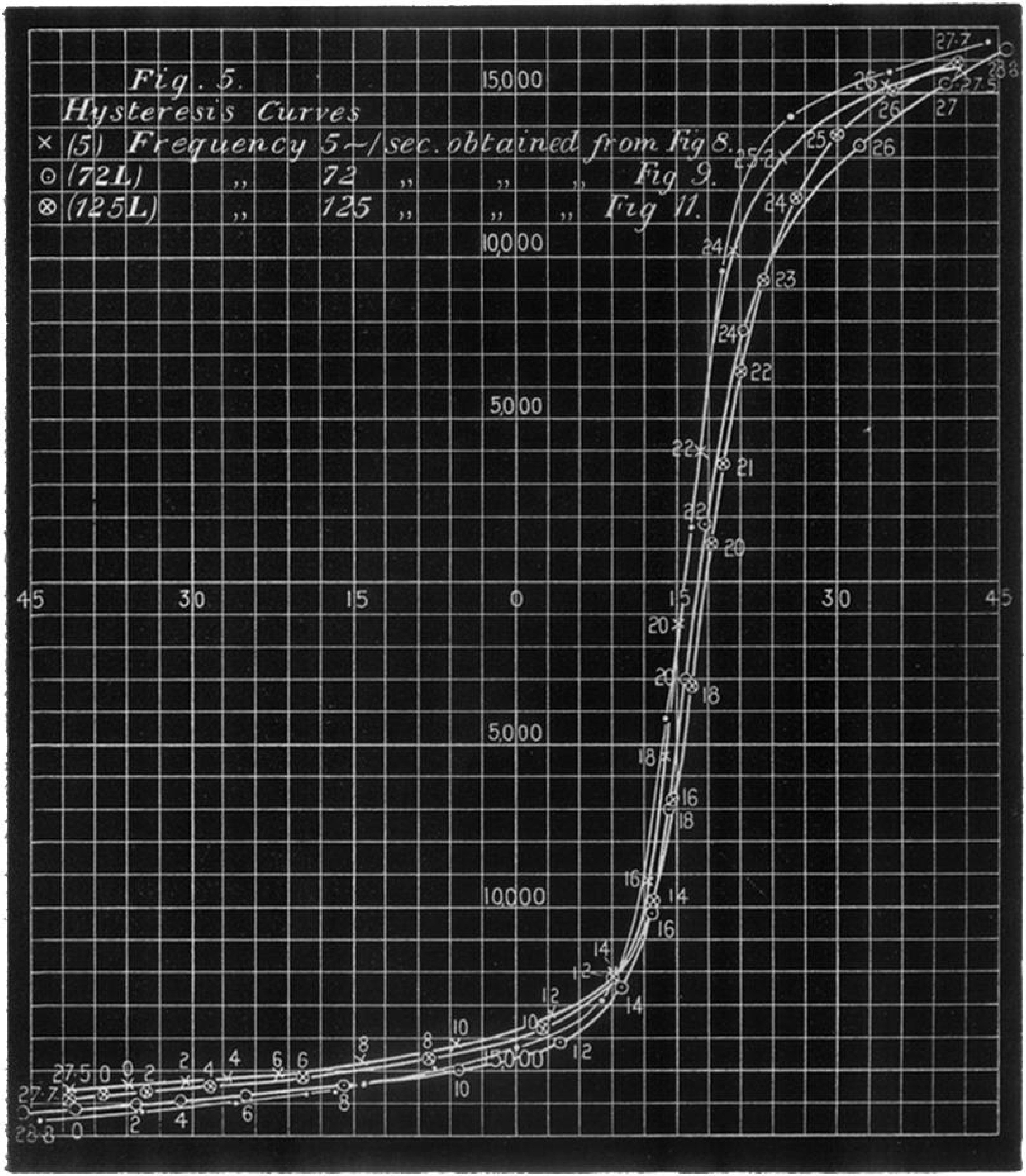


Fig. 5.
Hysteresis Curves
× (5) Frequency 5~/sec. obtained from Fig 8.
⊙ (72L) „ 72 „ „ „ Fig 9.
⊗ (125L) „ 125 „ „ „ Fig 11.
15,000
10,000
5,000
45
30
15
0
15
30
45
5,000
10,000
15,000

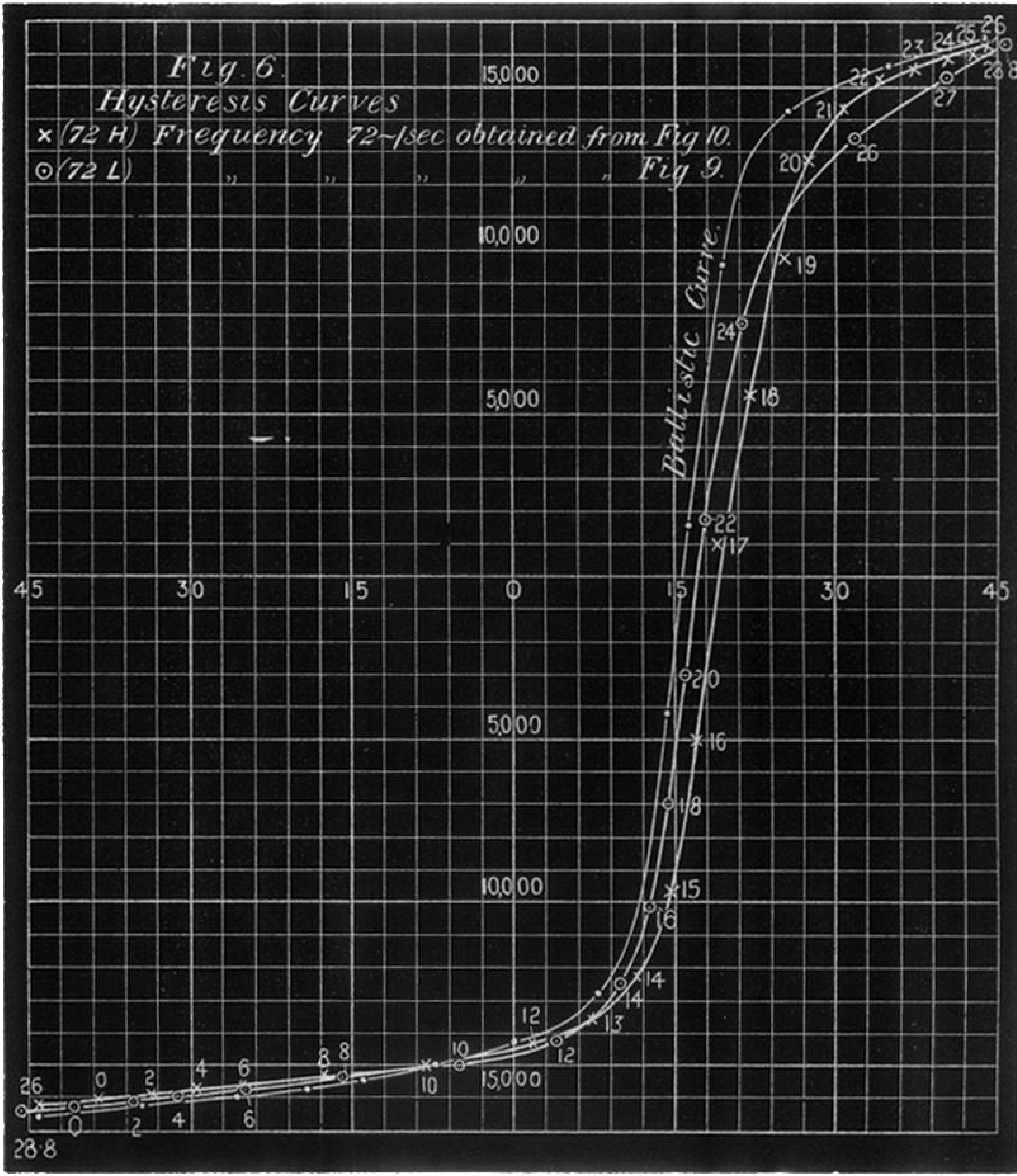


Fig. 6.
Hysteresis Curves
× (72 H) Frequency 72~/sec obtained from Fig 10.
⊙ (72 L) „ „ „ „ „ Fig 9.
Ballistic Curve
15,000
10,000
5,000
45
30
15
0
15
30
45
5,000
10,000
15,000
28·8

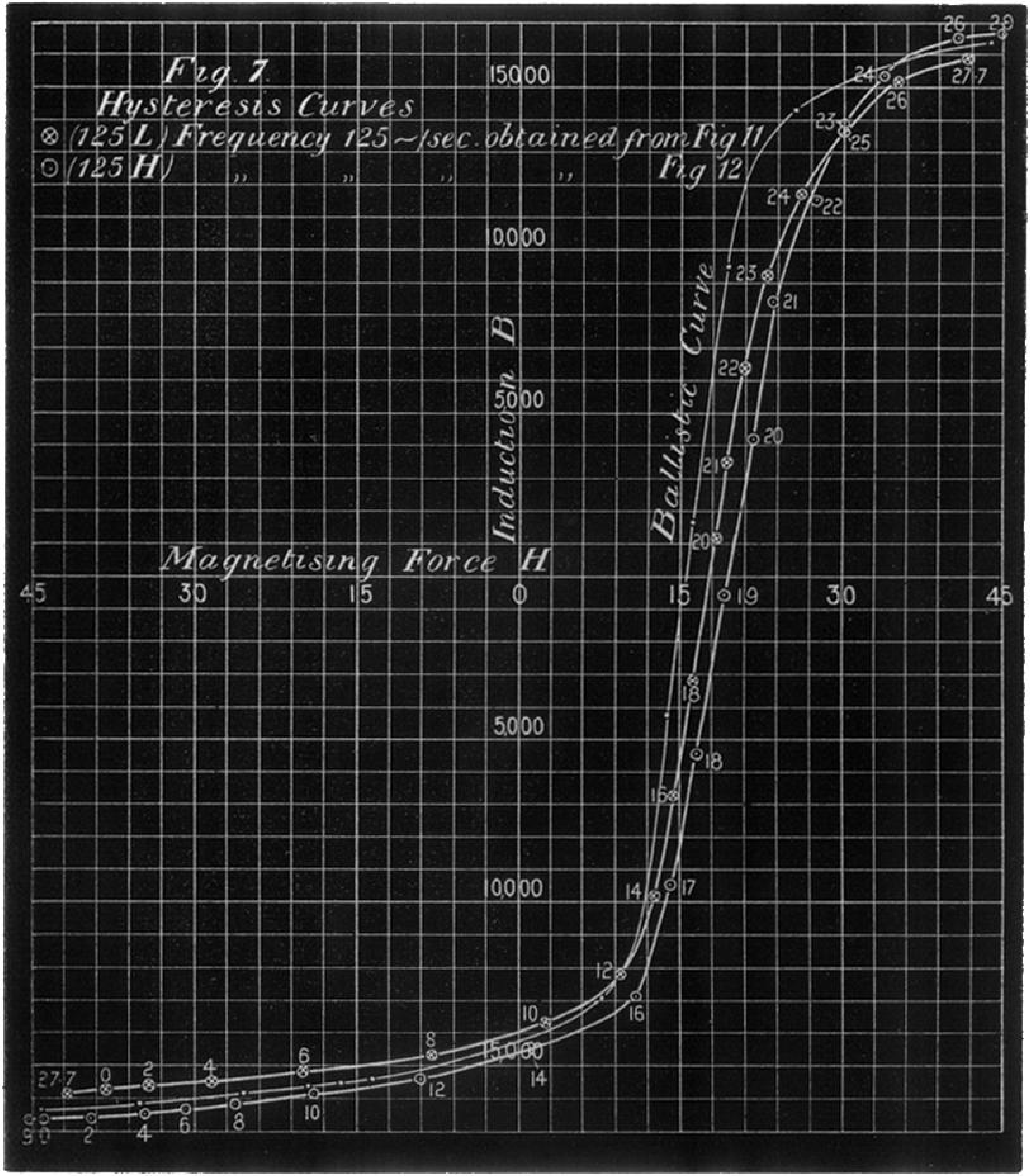


Fig. 7.
Hysteresis Curves
⊗ (125 L) Frequency 125~/sec. obtained from Fig 11
⊙ (125 H) " " " " Fig 12
Induction B
Magnetising Force H
Ballistic Curve
15,000
10,000
5,000
5,000
10,000
15,000
45
30
15
0
15
30
45

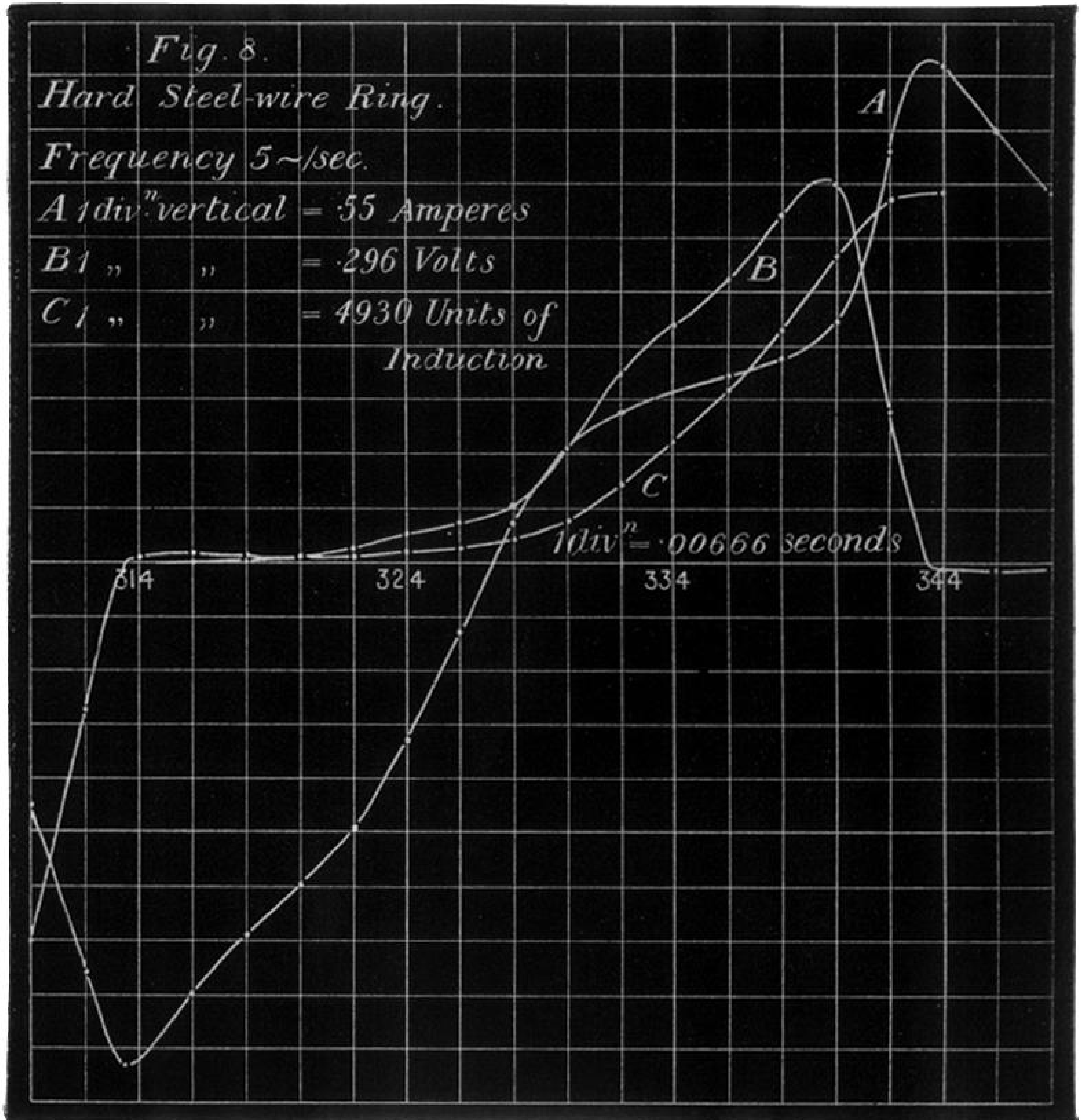


Fig. 8.
Hard Steel-wire Ring.
Frequency 5~/sec.
A 1 divⁿ vertical = ·55 Amperes
B 1 " " = ·296 Volts
C 1 " " = 4930 Units of Induction
1 divⁿ = ·00666 seconds
A
B
C
314
324
334
344

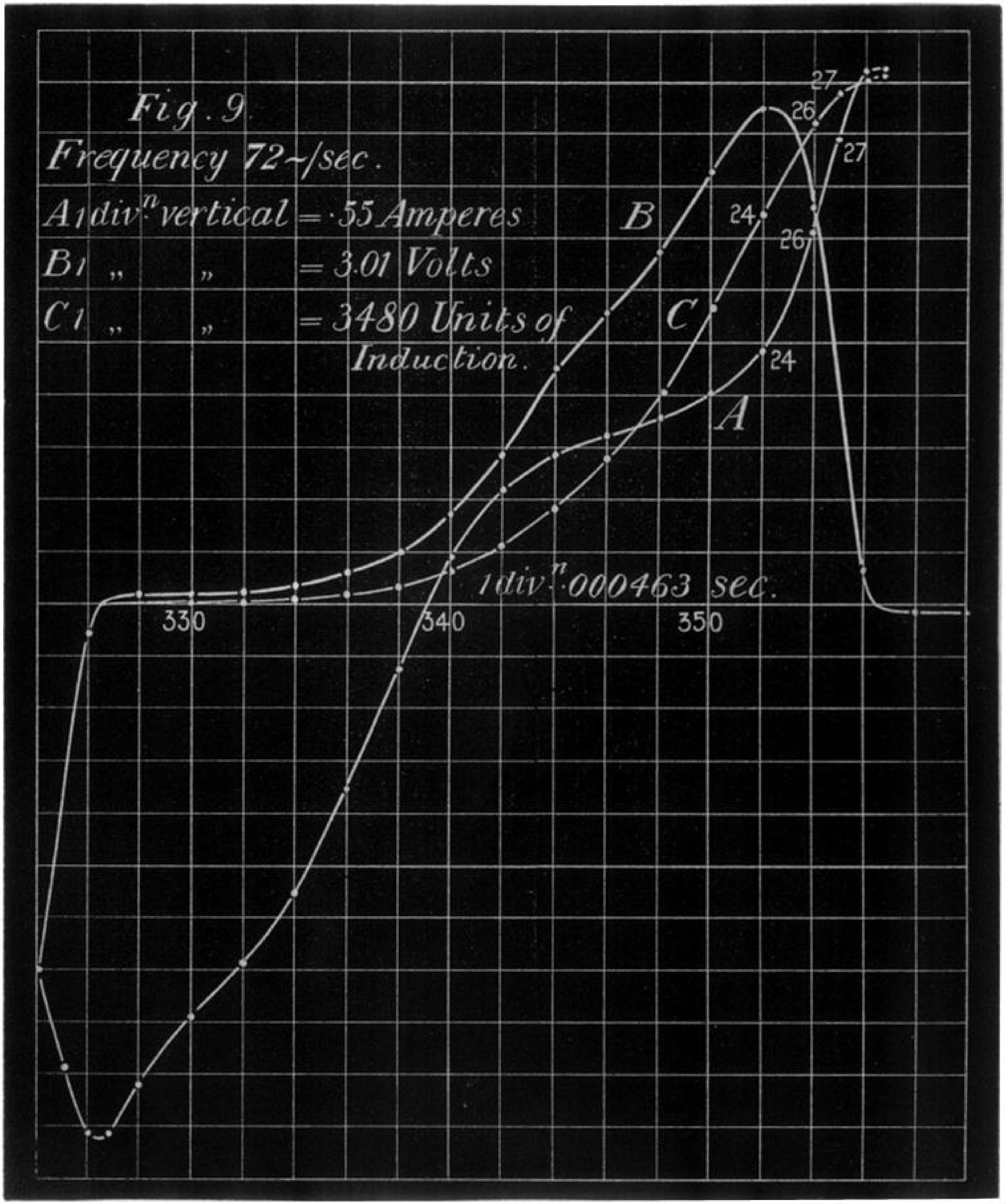


Fig. 9.
Frequency 72~/sec.
A 1 div^n vertical = ·55 Amperes
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27

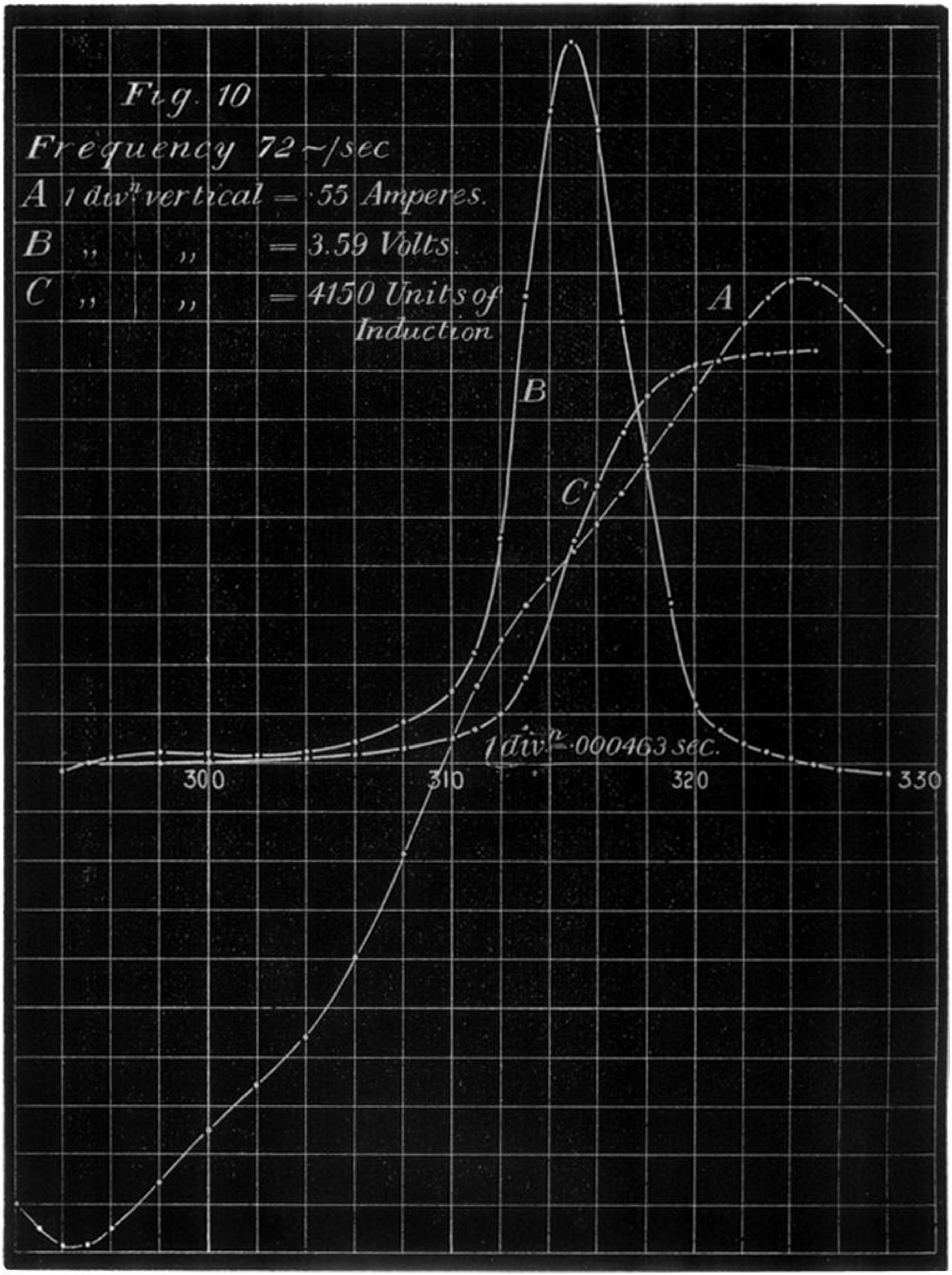
Fig. 10
Frequency 72 ~/sec
A 1 divⁿ vertical = ·55 Amperes.
B ,, ,, = 3.59 Volts.
C ,, ,, = 4150 Units of Induction
A
B
C
1 divⁿ ·000463 sec.
300
310
320
330

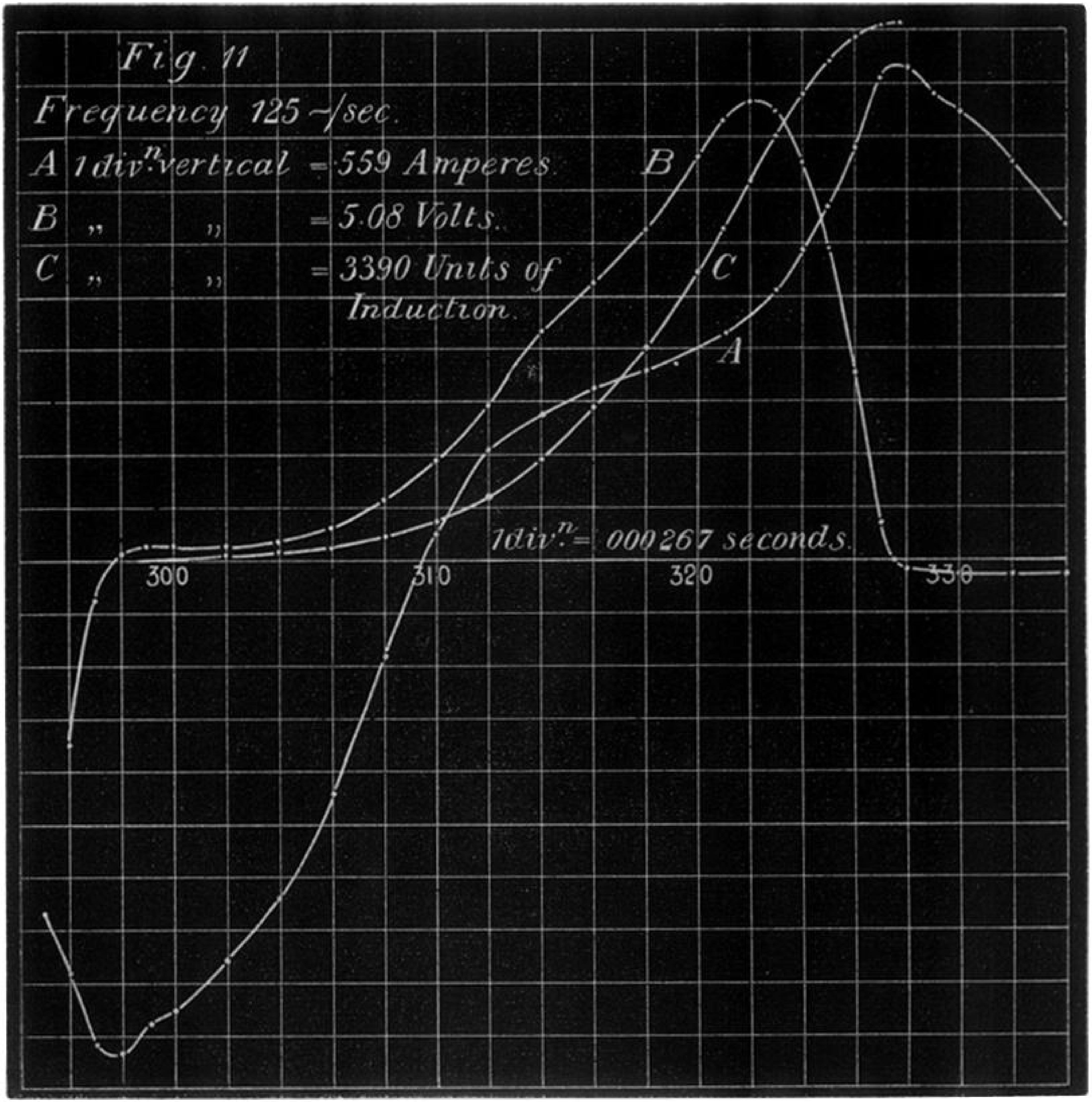
Fig. 11
Frequency 125 ~/sec.
A 1 divn. vertical = 559 Amperes.
B " " = 5.08 Volts.
C " " = 3390 Units of Induction.
B
C
A
1 divn. = 000267 seconds.
300
310
320
330

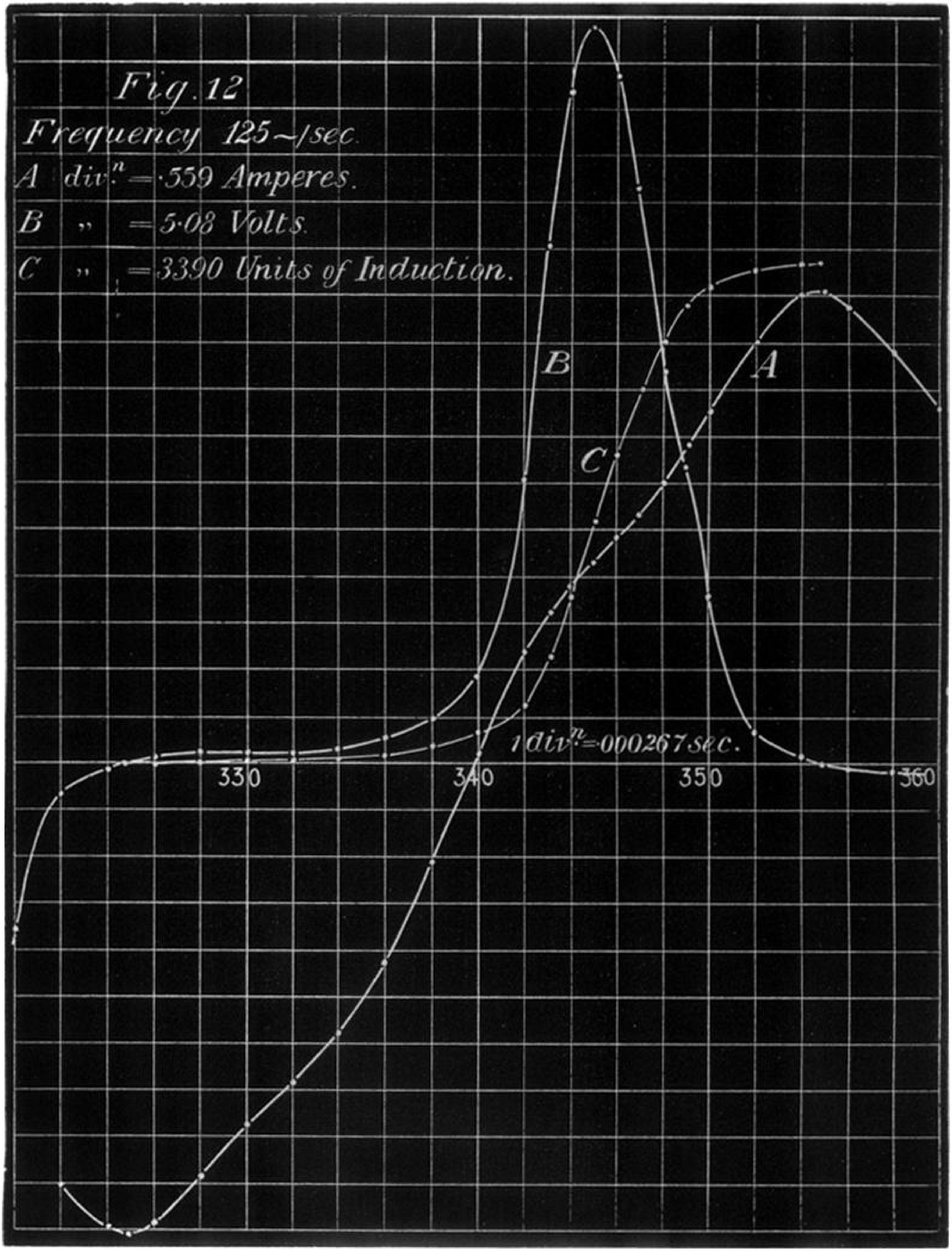

Fig. 12
Frequency 125~/sec.
A div.n = ·559 Amperes.
B ,, = 5·08 Volts.
C ,, = 3390 Units of Induction.
B
A
C
1 div.n = ·000267 sec.
330
340
350
360