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THE

PHYSICAL REVIEW.

ON THE EFFECT OF A MAGNETIC FIELD UPON CATHODE RAYS.

By Louis T. More and Lowell M. Alexander.

THE changes produced in the appearance of the discharge from the cathode of a Geissler tube when it is subjected to a strong magnetic field are very marked. It was generally supposed that the action of the magnetic field was to change the paths of the negative particles of the cathode rays into helices. But Professor Righi, after an elaborate series of experiments in which he caused the magnetized cathode ray to issue into a large tube, found such remarkable secondary effects that he abandoned the above idea as inadequate and proposed an entirely new hypothesis. He assumed that the magnetic field creates and makes stable a stream of electrically neutral doublets, each of which consists of an electron rotating in the same direction about a heavy, and positively electrified, gas ion; and that the magnetic field further exercises on the doublets a directive force to drive them to places of lower magnetic potential. When this stream, which he calls a "magnetic ray," has moved a critical distance from the cathode, the magnetic field is no longer strong enough to overcome the centrifugal force of the rotating electrons and the doublets break up. The secondary effects in the large tube he ascribes to the actions of their disassociated constituents.

Experiments[1] made in this laboratory, on the other hand, gave decided evidence against any such doublets being formed. In the second of these articles, on which the greater dependence can be placed, a hot lime, or Wehnelt, cathode was used and it was shown that all the secondary effects, upon which Professor Righi based the need and proof of his new theory, could be reproduced when there was no magnetic field at all. It was further shown that the "magnetic ray" differed only from the unmagnetized cone of rays, issuing from the hot-lime cathode, by bending

[1] More and Rieman, Phil. Mag., Vol. XXIV., p. 307; More and Mauchly, Phil. Mag., Vol. XXVI., p. 252.

towards or away from the pole of a test magnet instead of at right angles to it. This effect, evidently, would require no new theory as a stream of negatively charged particles moving in helices, will bend towards or away from the pole of an auxiliary magnet whether these particles are constituents of doublets or not. Other reasons were given to show that his theory was not only not necessary but that it was contrary to facts.

Professor Righi[1] has not abandoned his theory and he has, in these two new articles, published additional experiments and a rather severe criticism of our conclusions. He has undoubtedly proved that a minor point in one of our papers was incorrect where we stated that the phenomena do not occur unless complex or mixed gases are used in the tube. But his conclusion that his theory is a necessary one and that our ideas were based on results which were spurious and were due to poorly constructed apparatus we do not at all accept. It is unfortunate, perhaps, that the experiments we are about to describe have been so long delayed because we should have pointed out, while the matter was still fresh, the fact that Professor Righi could not even have read our articles carefully or he would not have based his most serious criticisms on charges obviously without foundation.

For example: he states, on pages 530 and 531,[2] that spurious effects similar to the phenomena of magnetic rays will be produced if there is the least spark produced in the main discharge circuit by a loose connection or otherwise. To produce the true effects the current must be a uniform and continuous one, produced by a static machine or high-tension battery, which condition will not be maintained if an induction coil be employed or if there be a spark gap anywhere else in the circuit. And then he adds: "It is not at all surprising that the physicists [More and Mauchly] have been deceived as they used currents produced by an induction coil and were evidently not careful to avoid possible spark gaps."

If the authors were deceived by spurious effects it could not have been for the reason given. On page 255[2] they state: "The principal thing which has hampered the work in the past was the use of an induction-coil or an electrostatic machine as a source of potential. The potential is then not sufficiently uniform, and the rays are rather unstable. The potential is too high, it cannot be measured accurately, and it produced too little current. All these defects are avoided by using a Wehnelt cathode in the tube, as we can then get a large current with a *low and steady potential from storage cells*." It seems rather hard to be accused of just the contrary when we adopted this method because Professor

[1] Righi, Phys. Zeitschr., Vol. XV., pp. 529 and 558.

[2] More and Mauchly, *l. c.*

Righi laid great stress on the periodic nature of the secondary effects of the "magnetic rays" and we wished to use a source of potential which could not of itself impress this periodicity on the discharge. We regret that we did not mention, what we supposed would be taken for granted, that we took care to have electrically continuous connections.

Again, his second principal criticism is that no "magnetic rays" can be obtained unless the direction of the magnetic field is transverse to the line of the discharge between the anode and the cathode. Now a glance at the disposition of our apparatus will show that the direction of the magnetic field coincides with the anode-cathode current. The issue is thus clear cut; whatever may be the case when a cold cathode is used, our results were and are absolutely without value unless his claim is wrong when a hot-lime cathode is used. To prove this point we shall first show by actual photographs that all the essential phenomena found by us are identical with those given in photographs in his book: "Strahlende Materie und Magnetische Strahlen."

If it is accepted that we are not now describing spurious effects, then we can give our additional evidence, and as frequently as possible by photographs, to show that the action of the magnetic field is to twist cathode rays into helical paths and not to create electrically neutral doublets. And let us state, at the beginning, that all the connections in the electrical circuits were soldered or were made by wires dipping in clean mercury except that a high resistance was used which consisted of wire dipping in acidulated water, an arrangement which Professor Righi permits. As a source of potential we used only a high-tension storage battery which had been first carefully put in excellent condition. And finally we made oscillograph records of the current which showed conclusively that there were no fluctuations in the current except those impressed upon it by the periodicity of the "magnetic rays."

As the apparatus used in these experiments is the same as that described in detail by More and Mauchly,[1] it will suffice to refer to that article and to give here only a brief statement of the essentials of the discharge.

The apparatus is shown in Fig. 1. The discharge circuit containing a water rheostat and the heating circuit for the cathode are both shown. A is the anode and C is the Wehnelt cathode on which a small spot of lime is brought to an incandescent heat. R is the large electromagnet giving a field strength of 2,000 units at a distance of 1.5 cm. from the pole.

A diagram of the typical portions of the discharge is indicated in the large portion of the tube. The portion a represents the "magnetic

[1] More and Mauchly, *l. c.*

ray"; *bcd*, the secondary or induced column. At *c* the virtual anode is marked; *b* and *d* are the two portions which bend under the influence of

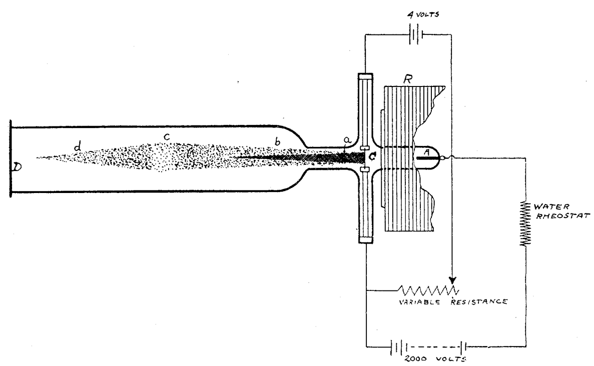


Fig. 1.

the pole of a test magnet as if a current of positive electricity were passing in both directions from the virtual anode, *c*.

As stated before, we wish to show by photographs that we are not dealing with spurious effects and the accompanying photographs should be compared with Professor Righi's as printed in his "Strahlende Materie," pages 239 and 242.

Fig. 2 shows the complete ray. In all the photographs the black band to the left is due to a sealing wax joint in the tube. The dark portion in the middle of the column is the virtual anode, *c*. The two parts of the secondary column are clearly shown. The "magnetic ray" is, however, not readily seen in this picture. But in Fig. 3, the "magnetic ray" is deflected by the pole of a test magnet held against the tube. The position of this pole is shown by the tip of the ray where it strikes the tube.

The curvature of the secondary column is shown in the next three photographs.

In Fig. 4, the pole of the magnet, which is seen behind the tube, bends the portion *d* in a circular arc which is convex downwards. In Fig. 5, the pole is at the virtual anode, *c*, and causes a bend of double curvature in the column; in other photographs this portion was split. In Fig. 6 the pole is located at *b* and the bend is a circular arc which is convex upwards.

Our tube also shows a fluorescent spot if the "magnetic ray" is made to strike the wall. The secondary column is periodic as shown by a rotating mirror, by oscillographs, and by a high-pitched musical note which it emits.

While many of the characteristics of the "magnetic ray" may be explained equally well by the doublet theory or by a stream of negative particles moving in a helical path, there are some properties which are not thus indifferent. If the rays from the cathode can be reduced to a sufficiently fine pencil of light, this line of light should be straight if Professor Righi is correct and it should be a spiral if the other view is the right one. Gouy[1] has shown the spiral form of these rays by an indirect method, and More and Mauchly also succeeded, at times, in making it visible. But we have now succeeded in controlling the effect so that it is readily obtained.

In order to obtain an easily visible spiral discharge the pressure, voltage, field current, and resistance of the water rheostat must all lie within certain narrow limits. The pressure must be rather low, between 0.001 and 0.004 cm. of Hg. The voltage has wider limits, as the spiral may be obtained by using from 200 to 1,000 volts. The magnetic field must be weak. The water rheostat must be adjusted so that the discharge just does not flash over with a very hot platinum strip. The spot of lime on the cathode strip must be very small, so that the electrons issue from a point source and thus form a very fine pencil of bluish light.

It is perhaps not possible to obtain a visible spiral discharge with a cold cathode, for the electrons are then not given out from a point, and it is practically impossible to obtain a discharge at the low gas pressures that can be used with the hot-lime cathode. Thus the spiral form is obliterated in the thick beam of light issuing from the cold cathode.

Photograph 7 shows the appearance of the spiral rays. The induced column may or may not be present when the discharge is spiral. When the pressure is very low, the "magnetic ray" comes out, without excitation of the large field magnet, not in a spiral but in a straight path. This is probably due to the residual magnetism of the coil, as there is a small iron pipe running through the center of the coil. If a test magnet, excited with a small current, is placed at right angles to the tube, the "magnetic ray" is not drawn towards the magnet, but is deflected towards a point on the glass 90° from the magnet. This condition is evidently due to the electrons not being wound on a spiral but travelling in approximately straight lines, and thus they would act as a flexible wire carrying current and be deflected at right angles to its axis and to the direction of the magnetic field. If the excitation of either the test magnet or the main magnet is increased considerably, the stream of rays becomes a spiral and it is then attracted directly to the pole of the test magnet.

This shows that the magnetic ray is identical with the cone of rays

[1] Gouy, C. R., Vol. CLII., p. 353; Le Radium, Vol. VIII., p. 129.

which is given out when the field coil is not excited, with the exception that in the latter case the electrons are not travelling in spirals.

As the magnetic field is not uniform, the pitch of the spirals increases in the weaker parts of the field. The spirals also are present on the anode side of the cathode, although they have a very small pitch, as they are in the strongest part of the field.

Direction of Rotation of the Spirals.

In the following discussion, a spiral that would advance with a clockwise rotation is called a right-handed spiral. One which would advance with a counter-clockwise rotation is called a left-handed spiral.

If the current in the main coil is in such a direction as to cause the pole of the magnet to attract a south pole of a compass, then on the anode side of the cathode the spiral was left-handed, and in the large tube it was right-handed. When the current in the coil was reversed the spirals reversed. The directions of rotation indicate that the particles composing the spiral stream are negative.

Measurements of the pitch of the spirals were taken at constant pressures while varying the discharge voltage and the field current. The field strength is assumed proportional to the field current.

Four curves are shown in Fig. 8 at a constant pressure of 0.003 cm.,

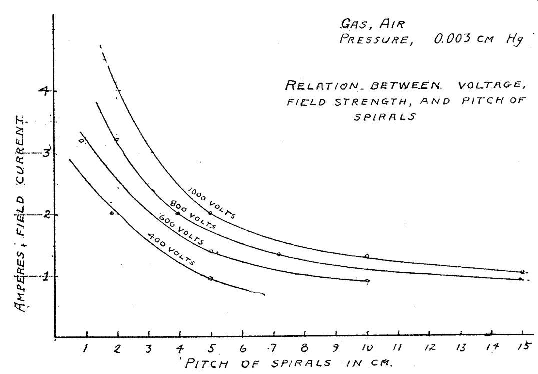
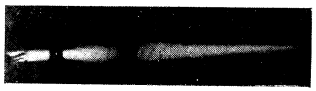


Fig. 8.

giving the relation between the field strength and the pitch of the first spiral in cm. in the large tube for four values of discharge voltage 1,000, 800, 600 and 400 volts. This shows that at constant voltage and pressure the relation between field strength and pitch of spirals is a rectangular hyperbola. The torque on the electrons decreases with decreasing magnetic field, and the translational force increases with the electric field, as is to be expected from theoretical grounds.



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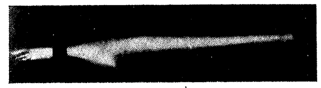

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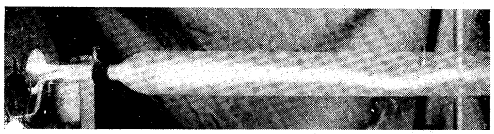

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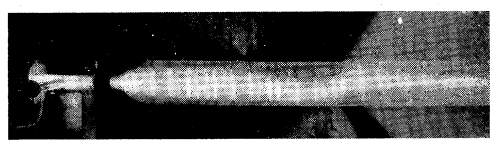

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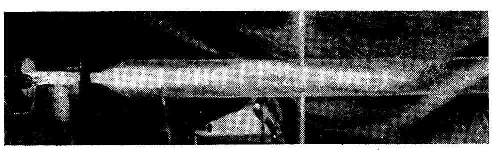

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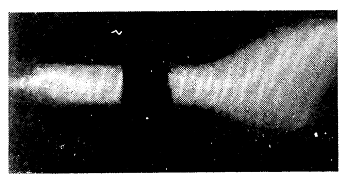

Fig. 7.

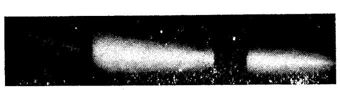

Fig. 10.

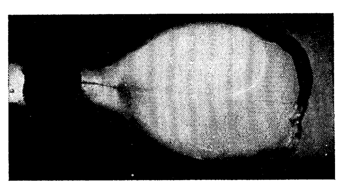

Fig. 11.

LOUIS T. MORE AND LOWELL M. ALEXANDER.

The diameter of the spirals was always roughly one tenth of the pitch. Well-defined spirals were obtained with voltages as low as 200.

Charge Carried by the Magnetic Ray.

Undoubtedly the final test of the two theories must rest with the electrical nature of the "magnetic rays." If they consist of a stream of doublets then they must be electrically neutral, but if they are deflected cathode rays they must certainly be charged with negative electricity. This difference has not been satisfactorily tested. Professor Righi states that he received them in a Faraday pail and found them to be electrically neutral. On the other hand, Thirkill,[1] by the same method, found them to be charged negatively. This difference is perhaps not surprising as in both cases the Faraday pail was placed in the large tube directly in the line of the rays. Because of intense ionization of the gas in this tube one might expect to collect in a Faraday pail either negatively or positively charged particles or both in varying proportions. To avoid this source of error an extension was inserted in the tube between the cathode and the wide portion. A branch tube 1 cm. inner diameter and 18 cm. long, was sealed into this new part as shown in Fig. 9. Into this

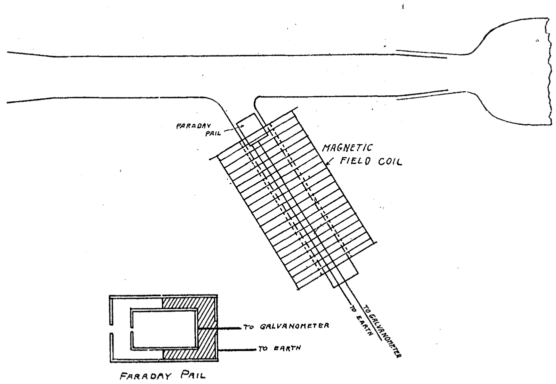

Fig. 9.

branch a very small Faraday pail was inserted and a magnetizing coil was wound upon it. By varying the current through this coil and moving it back and forth along the branch tube, the stream of "magnetic rays" could be projected against its wall or be drawn directly into the pail. At first, in order to measure the charge, an electrometer was tried, but as was the case in Thirkill's experiments, the readings were erratic. This is probably due to the intense ionization of the gas even in this branch tube, which renders it such a good conductor as to allow the charge to leak off immediately.

[1] Thirkill, Proc. Roy. Soc., 1909, p. 324.

The electrometer having been found unsuccessful, it was replaced by a galvanometer. The inner pail was connected to one terminal, the other being earthed. It was found that when the rays were deflected directly into the pail the galvanometer invariably gave a steady deflection, indicating a negative charge.

From these results there can be little doubt that the "magnetic rays" consist of slowly moving cathode particles twisted into a helix by the action of the magnetic field. It is, furthermore, easy to show by photographs that the "magnetic rays" are streams of negatively charged particles. A piece of copper gauze was placed inside the large tube about eight inches from the cathode and at right angles to the axis of the tube. A small wire connected to the gauze was led out, so that it could be connected to a source of potential, to an electroscope or to earth.

When the leading-out wire was insulated, only a very small proportion of the magnetic rays penetrated the screen. This is shown in photograph 10. When the leading-out wire was connected to an electroscope, a steady deflection was observed, which deflection was reduced when a positively charged rod was brought near it, and increased when a negatively charged rod was brought near. All of these indicate that the screen had received a negative charge from the rays.

In photograph 11 a screen is shown inserted at an angle of 45° to the axis of the tube. When this screen was connected to the cathode, the magnetic rays were deflected into a parabolic arc. The screen charges up negatively and the magnetic ray, which consists of slowly moving electrons wound on a spiral, is deflected by the electrostatic field.

Lastly, instead of the screen, a single wire was placed at right angles to the axis of the tube, with a leading-out wire, as before. Photographs, which are not printed because of lack of space, show clearly that the magnetic ray is a stream of negatively charged particles. When the magnetic field is weak the ray stops, with a flattened end, before it reaches the wire which has become negatively charged. If the discharge is then driven into the tube by increasing the field, the ray splits into a fork around the wire; if the field is made still stronger, these forks unite and leave a dark space completely surrounding the wire.

Pulsations in Discharge Circuit.

It was noted that when an earthed screen was placed over the tube, the cathode also being earthed, a tone was given out by the tube when the rays appeared. The pitch of this tone could be varied over wide limits, in the case of this tube over three octaves. The pitch was changed by the following methods:

1. By varying the magnetic field.

2. By varying the heating current through the platinum strip, thus liberating more or less electrons.

3. By changing the inductance of the wire connecting the screen to earth, by means of a variable inductance. The added inductance, varying from 0 to 50 milhenrys, changed the note by about one full tone.

4. By pressing the screen closer to the glass surface of the tube. This evidently shows a condenser action, the screen and the ray inside the tube acting as the two metallic plates, the glass tube itself being the dielectric.

An oscillograph was placed in series with the high-tension storage-battery circuit to measure the change of current. Oscillograms were taken when the tube gave out tones of different pitch, the pitch being determined in each case by means of a variable tuning fork. A 60-cycle voltage wave was superimposed on the current wave in order to measure the number of pulsations per second. It was found that in every case the number of pulsations per second in the discharge circuit was equal to the frequency of the tone given out by the induced column. For instance, in one case the tone was set one octave above middle C and an oscillogram was taken. By counting the pulsations on the oscillogram it was found that there were 510 per second, 512 being the frequency of the tone.

As this whole question of periodicity has been very carefully discussed by Dr. Ives[1] since our experiments were completed, it is not necessary to go further into the question.

Experiments on the Secondary Column.

Professor Righi not only refused to accept our conclusions in regard to the nature of the "magnetic rays" but he also asserted that we could not have obtained a true secondary column which was periodic and had a virtual anode. He states that such an effect is impossible unless the anode-cathode discharge takes place perpendicularly to the magnetic field. Our apparatus is designed so that they coincide. We have given photographs of this ray; we find that it is periodic both by the oscillograph and by the tone emitted; it also bends, as do his secondary columns, under the influence of an auxiliary magnetic field. There remains still one other proof; that is, by measuring the potential at various points in the column by exploring wires, to show there is a place of a positive potential with respect to both ends of the column.

[1] Ives, Phys. Rev., Vol. IX., p. 349, 1917.

Experiments with Exploring Wires.

The glass plate forming the end of the tube was replaced by a brass plate. Through the brass plate two small holes were bored and long glass tubes were passed through the holes and hermetically sealed. Platinum wires had previously been threaded in the tubes and sealed with a millimeter in length left protruding, to serve as collecting points. The other ends of the wires were connected to a Dolazelek electrometer. The two platinum exploratory points were located at points A and B about 20 cm. apart, A being the closer to the cathode. By varying the magnetic field and potential, the virtual anode could be located between the cathode and A and then be driven to a position between A and B, and finally to a point beyond B.

If the secondary column has a virtual anode, then in the first position A should be positive with respect to B.

As the virtual anode passes into the region between A and B, the difference of potential should decrease; be reduced to zero and then reverse, attaining a maximum difference when the virtual anode reaches B. After the anode passes beyond B, the point A should remain always negative with respect to B.

This experiment was repeated many times and the deflections of the electrometer confirmed the presence of a virtual anode.

The above effects were obtained with and without the use of a magnetic field, thus confirming the conclusion of More and Mauchly. According to Professor Righi's hypothesis of the formation of the virtual anode, a magnetic field is absolutely necessary. In his experiments he used a tube with a cold cathode, in which the emission of electrons can only be changed by altering the voltage across the discharge. Under these conditions he was unable to locate a virtual anode when no magnetic field acts. But Dr. Ives quite confirms our view by finding, even with a cold cathode, "that the Righi effects will be produced without either magnetic field or spark gap if the pressure in the tube is made low enough."

With a Wehnelt cathode, when no magnetic field is used, the position of the virtual anode can be changed by altering the temperature of the heating strip, thus increasing or decreasing the number of electrons emitted and the gradient of the electric field about the cathode. If the heating strip is at a moderate temperature, a small number of electrons are given out, and the gradient of the electric field will be at a maximum. Thus the electrons will accelerate very rapidly in the first few centimeters of their path. The electric field however falls off very rapidly and the electrons will slow down due to collisions.

Now Sir J. J. Thomson[1] states: "The ionization does not begin until the cathode rays have a certain amount of energy. It then increases rapidly, attains a maximum which, in the cases investigated by Kossel, was when the cathode rays had energy corresponding to about 300 volts, then diminishes slowly at first, but ultimately inversely as the energy of the cathode particle." Therefore, as the velocity decreases in the tube, the ionization increases until the virtual anode is reached. Beyond this point most of the electrons cease to ionize the gas, but they still have sufficient velocity to carry them to the end of the tube. The negative particles which result from the ionization move towards the far end of the tube, since they have a high mobility. The field however at the virtual anode is so weak that it causes only a slow drift of the heavy positive ions to the cathode, thus leaving a positive layer between the two negative ends of the tube.

Now suppose the temperature of the heating strip to be increased beyond a critical value. Under this condition more electrons are given out and the electric gradient is less steep on the far side of the cathode. The particles will not accelerate so fast, and as the field falls off the accelerating effect will be neutralized by collisions. In this way the velocity at which no ionization takes place will be reached sooner, and the virtual anode will move nearer to the cathode, shortening the whole ray.

If the number of electrons emitted be increased still more, the gradient decreases and the virtual anode continues to move towards the cathode, and will finally reach such a position that the electric field is strong enough to remove the positive ions as fast as they are formed, and the reddish-white or secondary column will disappear, leaving only the blue stream of cathode particles.

It is evident, if this explanation is correct, that the existence of a magnetic field is not necessary. Let us investigate the effect of the magnetic field. When a small magnetic field is applied along the axis of the tube, the negative glow is lengthened from a centimeter or two, to 15 or 20 cm.[2] Although the length of the secondary column is not necessarily changed, it is shifted as a whole towards the far end of the tube, carrying with it, of course, the virtual anode. The effect then is, that under a given difference of potential, the virtual anode is farther from the cathode when a magnetic field is acting than when it is not.

Now suppose a very large magnetic field to be applied. The length of the negative glow is increased only a small amount. The electrons

[1] Sir J. J. Thomson, Proc. London Phys. Soc., Vol. XXVII., p. 108.

[2] Conduction of Electricity through Gases, J. J. Thomson.

are wound into spirals of a very small pitch and the distance from the cathode at which they will cease to ionize will be shortened, the secondary column will be decreased in length and the virtual anode will be brought closer to the cathode.

In the same way as before, the virtual anode may be brought so close to the cathode by increasing the magnetic field that the positive ions will be drawn to the cathode,—the secondary column disappearing as before.

Thus, as the magnetic field is increased from a zero value, the distance of the virtual anode from the cathode increases, comes to a maximum, decreases, and finally disappears. Also since the same amount of ionization takes place over a shorter path due to the helical path of the electrons, the intensity of ionization will be increased, thus explaining the greatly increased illumination noticed when the magnetic field is applied.

We again wish to thank Mr. P. B. Evens whose great skill made much of our work successful.

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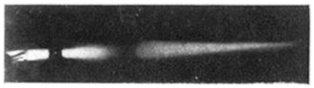

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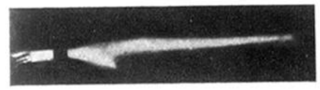

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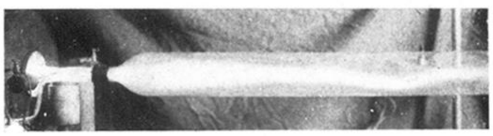

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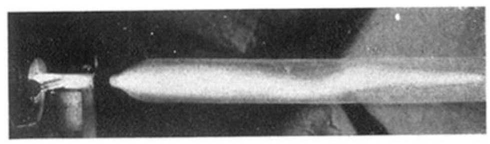

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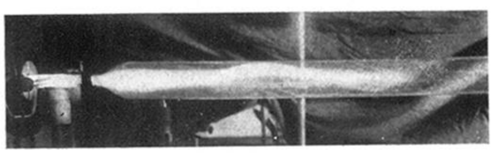

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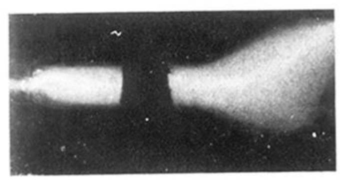

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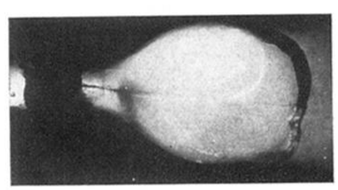

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