Effect of the Target on Breakdown in Cold Emission

By Willard H. Bennett
Mendenhall Laboratory of Physics, Ohio State University

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By application of a magnetic field in a certain way, the effects of the target on emission of electrons from a cold cathode could be separated from the effect of conditions characteristic of the cathode surface. Observations show that the condition of the anode has a large effect on breakdown.

THE design of tubes to give high velocity particles has been handicapped by the fact that destructive cold emission is apt to occur in the tube when potentials of the order of one million volts are applied.[1] Recent attempts to avoid this effect have been made but the complicated manners in which the high speed particles are to be obtained seem seriously to limit the magnitude of the useful current to be developed in such tubes.[2]

It is well known that when electrodes are well cleaned, destructive emission occurs only when the electric field somewhere on a cathode has reached the order of one million volts per centimeter, but the same amount of emission is given from electrodes which have not been heated in vacuum or otherwise cleaned or polished, at fields of the order of one hundred thousand volts per centimeter.[3] Little work seems to have been done to find out why this treatment makes so much difference.

Theoretical considerations[4] lead to the conclusion that the first measurable field currents (say, order of 10^{-10} amps.) should occur when the electric field at the surface of a cathode has reached the order of ten million volts per centimeter. Actually, with well polished or outgassed electrodes, such currents are observed at fields of the order of one million volts per centimeter. This is explained on the basis of Schottky's theory[5] of submicroscopic points or ridges on the surface of the cathode. There seems to be no essential difference, with regard to these first small currents, between thoroughly outgassed electrodes[6] and electrodes which have not been outgassed but only well polished.[7] The great, unexplained, discrepancy occurs with the breakdown in the two cases.

[1] W. D. Coolidge, J. Frank, Inst. **202**, 639 (1926); Lauritsen and R. D. Bennett, Phys. Rev. **32**, 850 (1928); Tuve, Breit and Hafsted, Phys. Rev. **35**, 66 (1930); Brasche and Lange, Naturwiss. **18**, 765 (1930); Zeits. f. Physik **70**, 10 (1931).

[2] Lawrence and Livingston, Phys. Rev. **38**, 834 (1931); Lawrence and Sloan, Phys. Rev. **38**, 586 (1931) and Proc. Natl. Ac. Sci. **17**, 64 (1931).

[3] Millikan and Shackelford, Phys. Rev. **15**, 239 (1920).

[4] Fowler and Nordheim, Proc. Roy. Soc. **A119**, 173 (1928).

[5] Schottky, Zeits. f. Physik **14**, 80 (1923).

[6] Eyring, Mackeown and Millikan, Phys. Rev. **31**, 900 (1928).

[7] W. H. Bennett, Phys. Rev. **37**, 582 (1931).

The term "breakdown" will be used in what follows to designate the change in the cathode which causes the current to change suddenly in order of magnitude without any change in the "measured field".[8] With well polished or thoroughly outgassed cathodes, the first breakdown always leads to new field-current characteristics having higher order values of current for a given field than the corresponding values of current before the sudden increase. Breakdown is not reversible.[9] It cannot be attributed simply to a sudden decrease of work function at the emitting surface, but one is forced to conclude that sharper submicroscopic points have been produced on the surface of the cathode.

Cases are known where measurement of the field-current characteristic did not show a breakdown[10] but these were all cases where the electrodes were thoroughly outgassed. In general, the less thoroughly the electrodes (either the cathode or the target of emission, or both) have been outgassed, the more severe the breakdown is.[11]

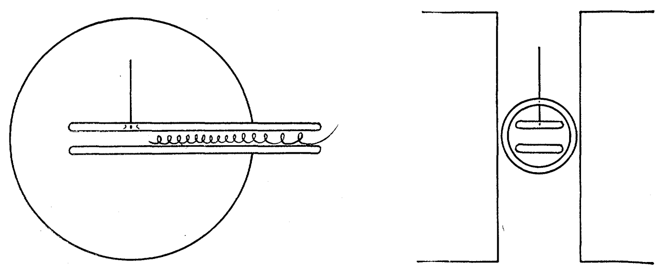

Fig. 1. Arrangement of electrodes in previous experiments.

The purpose of this investigation was to ascertain what factors are necessary for breakdown, and thus to be able to answer the questions: (1) why is breakdown so much more severe with unoutgassed electrodes; and (2) how can breakdown be eliminated from high voltage tubes in which the electrodes must be so large that heating to high temperatures in vacuum is impossible?

Experiment

In a previous experiment,[12] two parallel plane electrodes furnished an electric field which was nearly uniform in the center of the tube. A fine metal point was suspended in a hole in one of the electrodes. Currents drawn from the point were attracted towards the opposite electrode but were deflected by a magnetic field perpendicular to the plane of the figure. (See Fig. 1). Calculation of the path of an electron in perpendicular electric and magnetic fields shows that the path is cycloidal and the direction of drift is perpendicular to both the electric and magnetic fields. This path was clearly observed

[8] By "measured field" is meant the field calculated from the large scale geometry of the electrodes. Stern, Gossling, and Fowler, Proc. Roy. Soc. **124**, 700 (1929).

[9] Pits in the surface of the cathode have been seen with a microscope, after breakdown.

[10] Millikan and Eyring, Phys. Rev. **27**, 57 (1926). Wires I and II.

[11] See, also, Piersol, Phys. Rev. **31**, 444 (1928); and W. H. Bennett, reference 7.

[12] W. H. Bennett, reference 7, pp. 584–586.

traced on the side of the tube, as shown in the figure. When the point was allowed to project beyond the plane of the lower face of the upper plate, all the emission was confined to a small spot on the glass directly opposite the point along a magnetic line of force, but when the point was placed a little above that plane, the emission was thrown on the glass as shown.

In the new tube used in this investigation, a curved shield was used. The shield was in the shape of two-thirds of a cylinder, length four inches, diameter one and one-half inches, the missing third of the cylinder being cut parallel to the axis. The edges were turned back from the axis, and a slot was

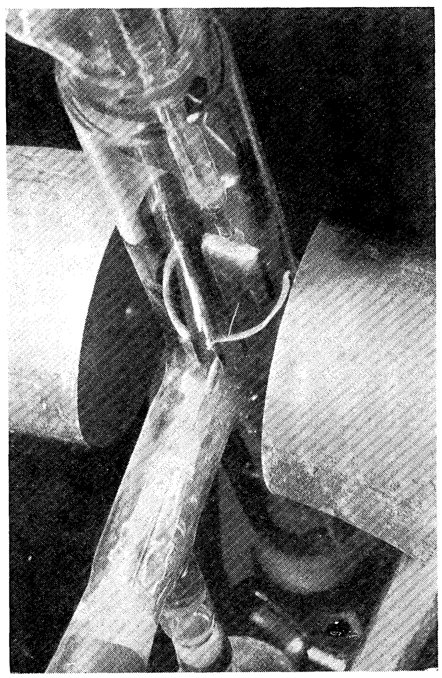

Fig. 2. View into end of tube.

cut in one end midway between the edges. The end of the shield with the slot is clearly visible in Fig. 2. The anode was four inches long and three-fourths inch wide. The edges of the anode were also turned back. The fine metal point was held in a glass sleeve through the slot in the shield, at distances from one to three millimeters from the anode.

In the vicinity of the anode and the plane AA (Fig. 3), the electric field will be practically uniform, but as an electron approaches a side of the anode, there will be an increasing component of the electric field towards the plane AA. The decrease in the vertical electric field will cause a decrease in the breadth of the cycloidal path instead of allowing the electron to fall farther towards the anode. The magnetic field thus confines the electrons to a region fairly centrally located over the anode and forces the electron to move along the tube away from the emitting point to some place outside the region of strong magnetic field. In this manner, the emission from the point can be prevented from striking the anode near the emitting point.

Pressures were measured on an ionization gauge which was attached to the tube at a place opposite the pumping outlet. Pressure readings were usually between $2 \cdot 10^{-5}$ and $1 \cdot 10^{-5}$ mm. Potentials were applied and currents were measured in the same manner as reported previously.[13] A ballast resistance of $3 \cdot 10^{7}$ ohms was used.

Observation

With all electrodes copper, or with a copper shield and point and a magnesium anode, it was observed that after breakdown and steadying the current (by decreasing slightly), the potential applied to the tube, the application of the magnetic field caused fresh breaks. On the other hand, with a

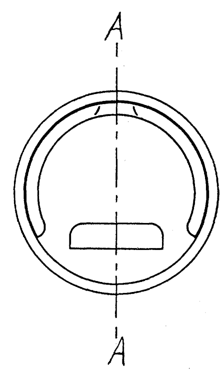

Fig. 3. Arrangement of electrodes in present experiment.

freshly mounted point, after breakdown and steadying the current, both in a strong magnetic field, the removal of the magnetic field caused fresh breaks. After the magnetic field had been changed through its full range of values (5000 gauss to -5000 gauss) and the current had been steadied, alterations of the magnetic field did not produce any further observable changes in the current. (Not exceeding five percent). The pressure usually decreased with such treatment from $2 \cdot 10^{-5}$ to $1 \cdot 10^{-5}$ mm.

With no magnetic field applied, after breakdown and steadying the current, the fluorescent spots on the anode never appeared at the place on the anode directly opposite the emitting point, but always all around this place, and frequently nearly out to the edge of the anode.

With the magnetic field applied, immediately after breakdown, spots appeared on the anode at a place near the emitting point, where they would have been expected for a pure electron stream with a magnetic field of about one-fifth the intensity used. In the conditions obtaining, the breadth of the cycloidal path for an electron varies inversely as the intensity of the magnetic field, and the distance of the emitting point was about four times the breadth

[13] W. H. Bennett, reference 7, p. 583.

of the path calculated for an electron. With the copper anode, these spots soon disappeared and all the emission went down the tube to the end of the anode farthest from the emitting point. With the magnesium anode, these

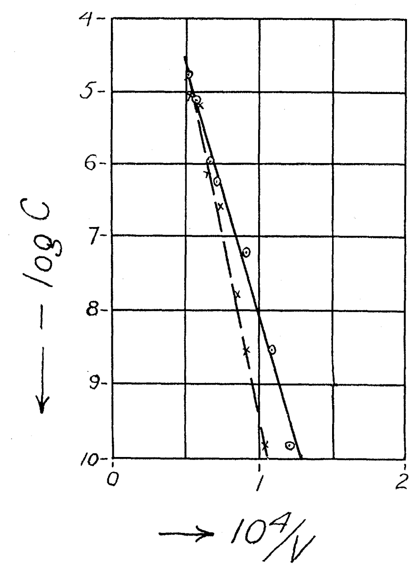

Fig. 4. Field-current characteristics with copper electrodes.

spots took longer to disappear. While the spots were visible on the anode near the emitting point, fluorescent streaks appeared on the glass walls of

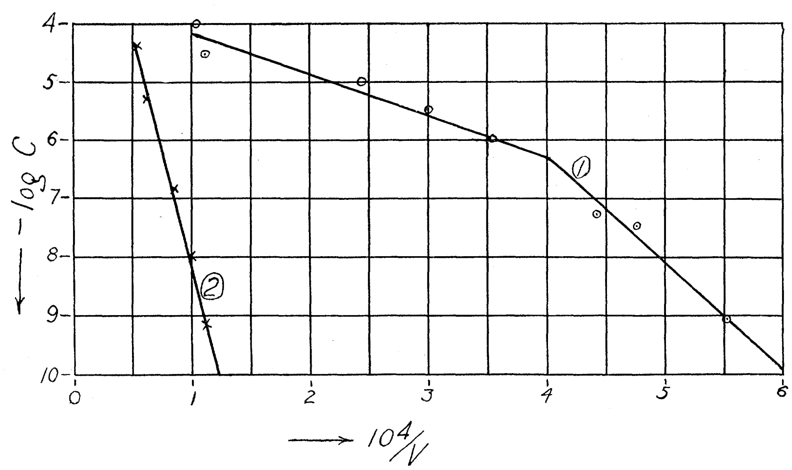

Fig. 5. Field-current characteristics with magnesium anode.

the tube at the end farthest removed from the emitting point. As the spot on the anode gradually faded and finally disappeared, the streaks at the far end of the tube did not seem to change much in shape or intensity.

Successively mounted copper emitting points, used with copper anode and shield, gave field-current characteristics which coincided on an average as well as the two curves shown in Fig. 4. No definite variation of the characteristics could be traced to variations in magnetic field or in pressure of the residual gas in the tube.

With a magnesium anode, immediately after breakdown and steadying the current, the emission followed a characteristic like that shown by curve 1, Fig. 5. The part of the curve under 10^{-5} amperes was reproducible, but as soon as the emission was increased to above this value, it rapidly fatigued to a new characteristic shown with curve 2, which remained stable thereafter.

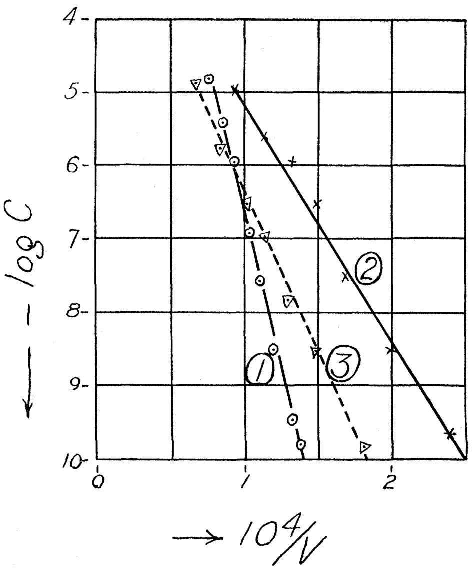

Fig. 6. Field-current characteristics with magnesium anode.

The test was now made of using a fresh copper emitting point and the magnesium anode, and producing breakdown in the strong magnetic field. The emission followed the characteristic shown with curve 1, Fig. 6. Removal of the magnetic field caused a new breakdown. After steadying, the emission followed curve 2, which was reproducible until the current was held above 10^{-5} amperes for about thirty minutes. After such fatigue, the emission followed curve 3.

Explanation

As mentioned before, theory indicates that all the emission comes from submicroscopic points or ridges. A natural imperfection of the surface, such as a bit of chemical impurity or a small pit should more probably give emission directed very nearly straight at the anode (see curve A, Fig. 7), if it lies in the position where the field first becomes sufficient to give measurable emission, because the "measured" field is a maximum at the point on the cathode where a straight electric line of force intercepts it.

The positive ions formed from residual gas or at the anode by the electron stream would in part, at least, follow the stream back to the emitting point. This bombardment of the emitting point by positives, if the current of the positives is not too concentrated, would eliminate the emitting point, perhaps by pounding it down. It is known that these first currents before breakdown are very erratic and frequently decrease suddenly to values too low to be measured and remain so indefinitely at fields just below that at which breakdown occurs.[14] It has been reported previously[15] that bombardment of the cathode by hydrogen positive ions, if moderate enough, eliminates the emitting points, although too much bombardment makes the cathode emit much higher currents for a given field than before. Thus if the potential applied to the tube is increased gradually enough, the fine points directing emission straght at the anode will be eliminated.

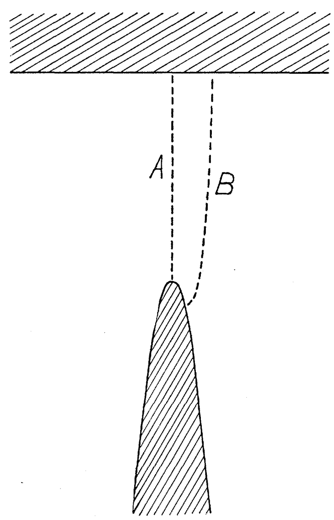

Fig. 7.

An imperfection which occurs somewhat asymmetrically with respect to the field (see curve B, Fig. 7) would give a stream of positives which would miss the emitting point, because the sharp curvature of the path of the electron stream near the point would serve to throw most of the positives out of the electron stream because of their high velocity and also because of their greater mass.

Perhaps the presence of these positives near the emitting point serves to increase the field at the point, thus momentarily increasing the emission. This however is not an important question right now. The important point is that by such a process as this, a stream of positives can bombard the cathode near the emitting point, but not directly at it, and this stream of

[14] This usually occurred with the unoutgassed spheres used in the previous experiment.

[15] W. H. Bennett, reference 7, p. 586–588.

positives can become very dense without eliminating the emitting point. We of course know that a dense stream of positives disintegrates the cathode surface by the process known as sputtering, and in this manner, holes are torn in the cathode surface. These may be expected to have ragged edges, and the edges would continue to be ragged even though the stream of positives continued to tear away successive particles.

This process would continue indefinitely because it would stop only when either (1) the source of the positives is nearly exhausted, or (2) the current is greatly decreased by sufficiently decreasing the field applied to the cathode.

Discussion

The magnetic control of the emission stream has furnished a means of varying any effects that the stream striking the anode may have, independently of any conditions characteristic of the cathode alone.

After the tube had been "cleaned up" by drawing currents of about 10^{-5} amperes while varying the magnetic field successively through its entire range of values, no luminous spot appeared on the anode immediately opposite the cathode. Sweeping the electron stream through the tube served to free most of the gas to be freed easily by such bombardment. Before such bombardment, a spot always was very clearly visible for a while, even though the magnetic field had an intensity at least four times that sufficient later to make the spot disappear. This shows clearly that gas freed from the anode, although not sufficient to increase appreciably the pressure in the tube as a whole, was ionized in the electron stream and because of the greater mass of the positive ions, served to keep the stream of electrons and positive ions in a path whose radius of curvature was about five times that of the path which a pure stream of electrons would have taken.

The higher concentration of positive ions to be expected earlier in the bombardment of any area of the anode would produce rupture more readily early in the history of a tube than later, on the basis of the explanation advanced above, since the supply of gas from any bombarded area of the anode would gradually become exhausted. This agrees with the observation that ruptures when once started continue indefinitely but become gradually less frequent.

The fact that the current becomes steady when decreased to one-tenth or less the average value during the breakdown, agrees well with the explanation because the concentration of positive ions will decrease by at least this ratio. This steadying may be due in part to the ability of a stream of positives of lower concentration to pound down irregularities without producing rupture.[16] The gradual decrease of emission reported by Millikan and Eyring[17] and called "conditioning" was apparently due to such a pounding down of irregularities by streams of positives of low concentration. Breakdown always occurred if the electrodes had not been outgassed. The few cases where no

[16] This effect is apparently present when there is no breakdown.

[17] Millikan and Eyring, reference 10, p. 55.

breakdown was reported occurred only in experiments where the anode had been thoroughly outgassed.[18]

The effect of a magnesium anode on the characteristic indicates that some substance, perhaps sodium, has travelled from the target to the cathode and reduced the work function. This effect agrees with the effect of a magnesium anode found in the previous investigation[19] if one considers that any submicroscopic point is much more likely to give emission along a straight electric line of force, between the spheres (which are effectively parallel plane plates where the emission is taking place) than in the case of point and plane.

It is somewhat obscure just what effect outgassing the cathode may have beyond evaporating from the surface impurities having high enough vapor pressures.

As the result of this investigation it may be concluded that the breakdown in cold emission, at pressures of 10^{-5} mm or less, is due to a stream of positive ions with high velocity, which is produced by an initially small electron current striking the target of the emission. Elimination of cold emission from high voltage tubes, if unoutgassed electrodes are to be used, seems to depend on preventing the positives leaving the target from hitting the cathode with high velocities. A means of accomplishing this is being incorporated in the design of a million-volt tube to be built in this laboratory.

The writer wishes to acknowledge the able assistance of Mr. Eugene V. Rasor in assembling and calibrating the apparatus used in this investigation.

[18] In Piersol's experiments (reference 11, p. 444) breakdown occurred in spite of the fact that the anode had been baked, but breakdown occurred only when the current exceeded a certain rather high value, (10^{-3} amperes).

[19] W. H. Bennett, reference 7, p. 588–589.

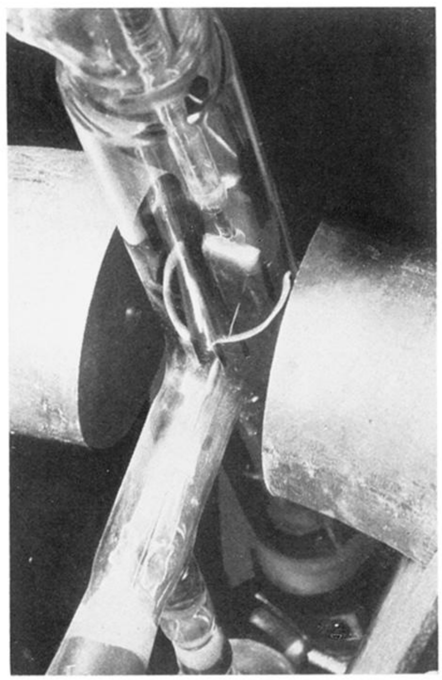

Fig. 2. View into end of tube.