Electrical Explosion of Wires in Vacuum

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Results of an investigation of electric explosion of wires in vacuum are described. It is shown that regardless of the initial shape of the wire the explosion products propagate as in an ordinary explosion, in a direction normal to the surface of the wire. If the voltage across the capacitor of the explosion circuit is relatively low, the vapor streams, as in the case of an explosion in air, from layers that range themselves perpendicular to the wire. It has been established that at high capacitor voltages the motion of the vapor streams affects the distribution of the discharge current in the space around the wire. A qualitative explanation is given for the observed effects.

1. INTRODUCTION

MANY investigations [1-5] have been devoted to electric explosion of wires in air and in various condensed media, but explosion of wires in vacuum still receives little attention. It would be interesting to investigate this phenomenon because the absence of the perturbing effects of the surrounding medium and the ready condensibility of the metal vapors could make it possible to obtain much additional information concerning the mechanism of the wire explosion to investigate the streams of the explosion products, to study the effect of the motion of these products on the spatial distribution of the discharge about the wire, etc.

We give below the results of experiments on the explosion of wires in a vacuum of approximately 10^{-5} mm Hg in a relatively large chamber.

There is no need for a higher vacuum, for further reduction in pressure does not affect the observed phenomena.

2. PROCEDURE AND EXPERIMENTAL RESULTS

Reference 3 gives the electric diagram of the set-up used in the experiments described below. A cross section through the explosion chamber is shown in Fig. 1, where *1* is the body of the chamber, *2* the high-voltage electrode, and *3* the wire under investigation; the linkage *4* serves to connect the chamber to the vacuum pump. The inside walls of the chamber were covered with a thick layer of lampblack to prevent reflection of light. Both flanges *5* are equipped with symmetrically-located windows of thick plane-parallel glass through which the explosion is photographed. The experiments were performed principally with copper wires. The explosion circuit comprised a 1.2-microhenry inductance and a four-microfarad capacitor.

In the investigation of the explosion-product condensation the wire was enclosed in a coaxial aluminum screen. A time exposure of the explosion was made in the natural light of the discharge in a direction perpendicular to the axis of the wire. The explosion picture was scanned with a mirror through a slit placed transversely through the wire near its center. The corresponding photographs are shown in Figs. 2–10.

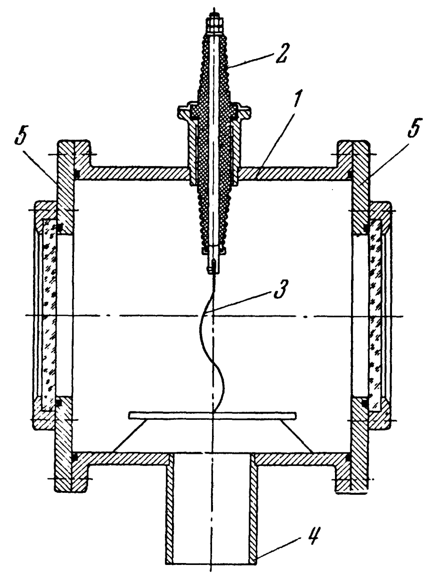


FIG. 1. Diagram of a vacuum chamber.

Figures 2–9 show the photographs of the condensates and of the time-exposures for copper wires in vacuum. Figure 2 shows a part of the aluminum screen coated with the explosion-product condensate from a straight copper wire. It is seen that the condensate forms stripes of constant height over the entire length of the screen. The stripes are perpendicular to the wire, and the height of the condensate is almost equal to the length of the wire. This indicates a radial distribution of the vapor streams from the wire. Figure 3 shows the developed screen with the condensate from an exploded wire bent in an arc; the ends of this arc lie on the axis of the screen. As can be seen, the height of the condensate goes in this case through two unequal maxima and two minima over the length of the screen. The two maxima are located where the plane of the bent wire intersects the screen, the greater maximum being on the convex side of the wire arc, and the smaller on the concave one. The two minima are closer to the smaller maximum and are symmetrical about it. It follows from simple geometric considerations that the geometric locus of the normal projections of the surface points of the wire on the screen reproduces the form and dimensions of the condensate with sufficient accuracy. This leads to a general conclusion that the products of the electric explosion of the wire propagate in directions normal to each point of its surface, regardless of the initial shape of the wire. It should be noted that this propagation of explosion products is similar to the usual explosion caused by strongly stretched charges.

It is evident that under these experimental conditions only the leading front of the vapor stream moves in a high vacuum, and the remaining portions of the stream move in a lower vacuum. Nevertheless, as can be seen from the photographs enclosed, boundaries of the condensate remain distinct and reproduce well the stratified structure of the vapor streams. This is possible only if the vapor streams move at very high radial velocities. Experiments with a ballistic pendulum have shown that the average vapor-stream velocities in our conditions reach approximately 2×10^5 cm/sec.

It must be noted that the stratification of the explosion in vacuum, as in air, is characterized by a certain periodicity, which is well noticeable in the structure of the condensate in Figs. 2 and 3. Fig. 4, obtained with six kv on the capacitor, shows clearly the stratified scattering of the explosion products. The same photographs exhibit also a certain stringing of the charge around the wire (the diameter of the string is approximately 4 millimeters). Fig. 5, obtained with 4 kv on the capacitor, shows that the wire did not have a chance to scatter during the discharge time of the capacitor and assumed a clearly pronounced wavy form owing to the shock compression caused by the rapid heating. No stringing of the discharge is noted

FIG. 2. Part of aluminum shield on which the wire-explosion product condensed. Wire diameter 0.2 mm, length 60 mm. Capacitator voltage $U_0 = 40$ kv.

FIG. 3. Developed view of screen with condensed wire-explosion products. Wire 0.3 mm in diameter and 45 mm long, bent in an arc of 50 mm radius. $U_0 = 40$ kv.

here. The attached pictures are good illustrations that the mechanism described in Ref. 4 for the electric explosion of wire in air is correct.

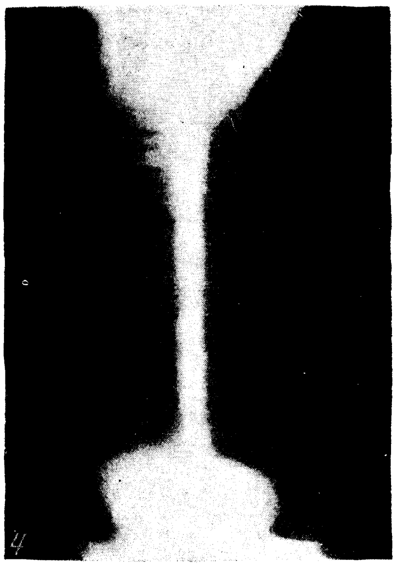


FIG. 4. Wire 45 mm long, 0.15 mm dia. $U_0 = 6$ kv.

Figures 6 and 7 show examples of integral photographs of explosion of straight wires. The signs + and – indicate the positions of the high-voltage and grounded discharge electrodes. What is striking about these photographs is that although they represent a violent explosion process, they exhibit clearly certain discharge states that are, so to speak, stabilized. The physical interpretation and the time sequence of the appearance of these states can be represented as follows. The center of each photograph shows the image of the still unexploded wire, related evidently to the initial stage of the discharge. As can be seen, the wire is surrounded in this stage by a thin layer of discharge, which glows more brightly than the wire itself. It is indeed its small thickness that causes the glowing layer to produce a brighter image at the edges of the wire, and the greatest thickness of the layer is consequently projected on the photographic plate. The fact that the discharge is concentrated in a thin cylindrical layer about the wire can be attributed to compression of the discharge around the wire by the strong magnetic field produced by the current reaching hundreds of thousands of oersteds (see below) at the surface of the wire. In view of the high discharge power the wire is almost instantaneously transformed, toward the end of this stage, into a high-pressure gas of high heat content and of almost the density as the wire. Under these conditions, as is known from the theory of explosive processes [6], the wire vapors scatter radially into the vacuum at high velocities. As the discharge develops further, each photograph shows the image of a thin-wall glowing cylinder, which flares out towards the electrodes, always more towards the high-voltage electrode than toward the grounded one, regardless of the polarity.

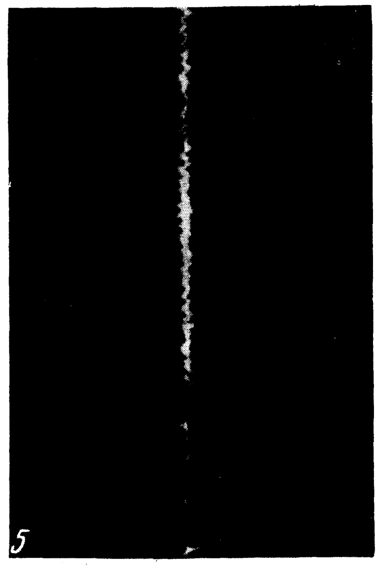


FIG. 5. Wire 150 mm long, 0.15 mm dia. $U_0 = 4$ kv. Capacitator 10 microfarad.

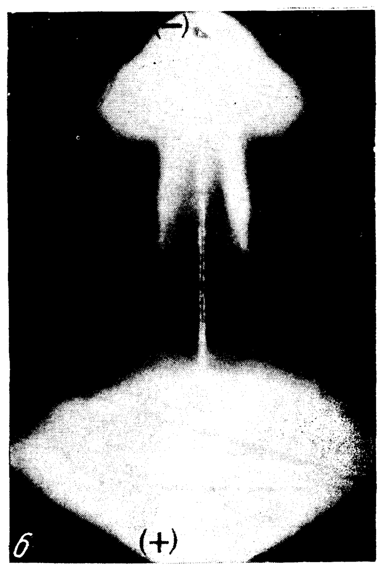


FIG. 6. Wire 45 mm long, 0.15 dia. $U_0 = 20$ kv.

Assuming that the glow of the discharge must under these experimental conditions be due to the flow of current through the gas, it is possible to deduce from the distribution of the brightness in the second glowing layer, (from the sharp increase in the brightness towards its edges) that in this discharge stage the total current is concentrated principally in the thin glowing layer (second layer), bounded on the outside and on the inside by two coaxial surfaces of revolutions.

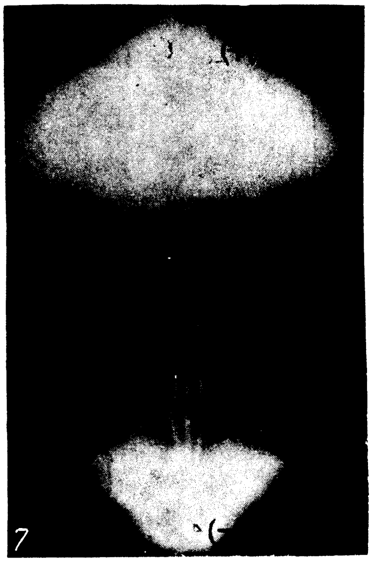


FIG. 7. Wire 45 mm long, 0.15 mm dia, $U_0 = 30$ kv.

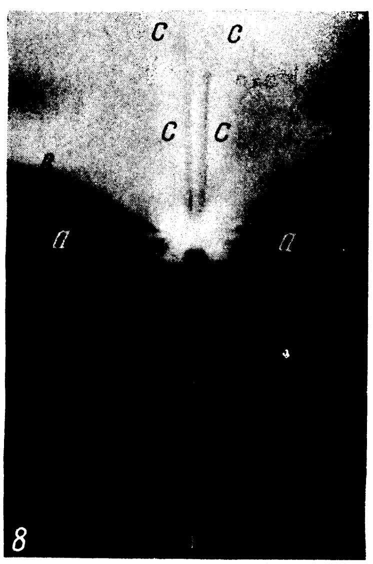


FIG. 8. Wire 90 mm long, 0.15 mm dia, $U_0 = 35$ kv. A plexiglass plate measuring $1 \times 100 \times 100$ mm was placed transverse to the wire.

Figures 6–10 are time-exposure and mirror-scanned photographs of wires exploded in vacuum.

Figure 7 shows that increasing the capacitor voltage not only increases the radial dimensions of the second glowing layer, but produces also a third layer coaxial with the second. In the case of longer wires, several third layers are produced in sequence along the wire. The third layers are sometimes internal branches of the second layer.

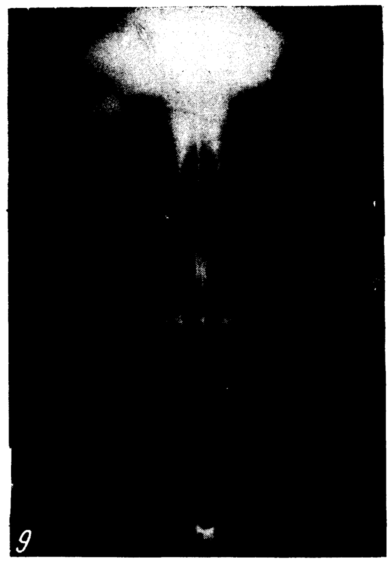


FIG. 9. Photograph analogous to that of Fig. 8, but with 20 mm hole in the plate and $U_0 = 30$ kv.

FIG. 10. Mirror scan of explosion of wire 90 mm long, 0.15 mm dia, at $U_0 = 30$ kv (full size).

Decreasing the wire diameter reduces the radial dimensions of the glowing channels as shown in the corresponding photographs. If the exploded wires are bent in an arc, the generatrices of the glowing channels are similarly bent. An axial time-exposed photograph of an exploding wire with right angle bends on the ends shows an almost-uniform glowing circle around the wire.

All the time-exposed photographs obtained by us indicate the presence of brightly glowing vapor streams originating at both discharge electrodes. Assuming the duration of the glow not to exceed the discharge time of the capacitor (40 microseconds) the average velocity of these streams parallel to the wire amounts to 10^4 cm/sec. Interaction with the radial streams apparently causes these longitudinal streams to slow down in an axial direction and to accelerate in a radial direction.

We proposed that the main cause of the formation of the glowing channels described above is the radial motion of the wire vapors in the strong magnetic field of the current. To check this premise, we set up experiments to determine how disturbances of the vapor streams and forced redistribution of the current around the wire would influence the effect under investigation. Figure 8 illustrates the explosion of a wire across which an insulating plate of organic glass is placed. The wire passes through the center of a 3 mm hole in the middle of this plate. In the photograph, the projection of the plate coincides with the illuminated line *aa*. As can be seen, introducing the insulating plate results in a strong disturbance to the radial vapor streams and in addition to changing the integral picture, it also causes a considerable redistribution of the discharge current. The increased current density causes the maximum brightness of the glow to occur in the region of the hole. From the structure of this region it can be seen that the current density is not uniformly distributed over the cross section of the hole: it increases towards the edges of the glowing cones that lead upwards and downwards from the plane of the hole. In the upper portion of the discharge, the current first flows over the conical channels *bb* (outside cones) and *cc* (inside cone), which result from the reflection of the radial vapor stream from the edges of the hole. Both these cones merge in the upper base (where the radial streams are still undisturbed) with current channels analagous to the second and third channels of Fig. 7. The second channel, owing to its considerable spreading, is not very pronounced on this photograph, but it can be easily distinguished on the corresponding negative.

Located over the bases of the cones is a region of sufficiently bright diffused discharge glow due apparently to the fact that the presence of the insulating plate in this region diverts a portion of the current to the nearest walls of the grounded chamber causing it to flow over the radial streams of the vapor. Here one must expect the current flowing through the radial vapor streams to scatter some of the vapor atoms in an axial direction. After the wire explodes, the upper portion of the plate actually becomes covered by noticeable deposit of copper, while below, where there is no noticeable discharge glow, and where consequently the radial streams are hardly disturbed by the current, the plate remains quite clean. The deposit above has a sharp boundary which is a circle of equal diameter as the upper base of the cone *bb*, and which is concentric with the hole in the plate. The deposit is much thinner inside the circular boundary than outside. On the circle itself the thickness of the deposit has a very sharp and relatively high maximum, this being apparently due to the additional material carried away by the copper ions from the section of the second glowing channel. The photometry curve for the copper deposit, taken with transmitted light along one of the diameter of the boundary circle (Fig. 11), illustrates well the deposit structure described below. The presence of a round deposit boundary of an increased thickness confirms the above hypothesis that the current is concentrated in thin-layered cylindrical channels.

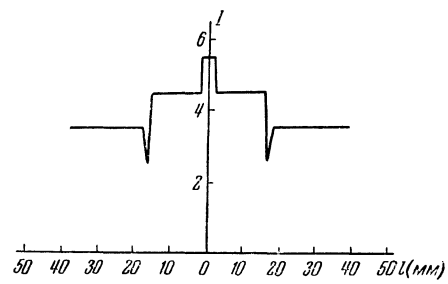
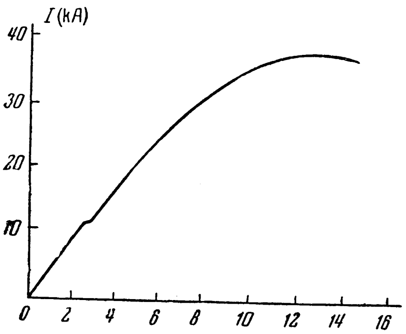


FIG. 11. Photometry curve of copper deposited on insulating plate. I—intensity of light in relative units, l—distance from center of hole in plate.

In the region between the plate and the grounded electrode one can also see a very weakly glowing channel (approximately cylindrical in shape), which is a continuation of the second upper channel (it is more distinguishable on the corresponding negative). The weak glow of this channel and its smaller radial dimensions (compared with the second upper channel) must be attributed to the smaller current flowing in the region under consideration owing to the presence of the insulating barrier, since the explosion conditions for the wire, and consequently the velocities of the radial vapor streams, are identical on both sides of the insulating plate.

Figure 9 shows an explosion with a 20 mm round hole in the insulating plates. Here the channels are seen more clearly. They pass freely through the large hole, experiencing thereby a certain deformation. The radius of the second channel becomes somewhat smaller in the vicinity of the hole, and the third channel is discontinuous as it passes through the plane of the hole. The deformation of the second channel is apparently due to the lower velocity of the radial streams due to their collision with the edges of the hole.

If the non-conducting plate transverse to the wire in Fig. 8 is replaced by a conducting plate, insulated from the chamber walls of equal size and with the same size hole, the channels remain the same as in the absence of the plate, as can be seen from the corresponding photograph. Only in the direct vicinity of the conducting plate do the channels become discontinuous, probably owing to a reflection of the vapor streams from the edges of the hole. Here, too, a copper deposit of noticeable thickness is formed only on the side of the positive electrode, with hardly any deposit on the negative-electrode side.



abscissa: t (microsec).

FIG. 12. Oscillogram of current for wire explosion in vacuum. Wire 45 mm long, 0.15 mm dia, $U_0 = 25$ kv.

Figure 10 shows the wire explosion in vacuum, scanned from left to right with a mirror through a transverse slit. The speed of the image along the photograph film is 2.2×10^5 cm/sec. Starting at the bottom, the photograph shows the glowing wire in its state prior to the start of the explosion. Towards the end of the explosion, the glowing region starts moving rapidly upwards in a radial direction (speed of displacement greater than 5×10^5 cm/sec). The displacement is then slowed down and the glowing section settles at a certain distance from the wire image. This evidently corresponds to the position of the second current channel (the lower half of this channel is outside the photographed area). The glow from the stabilized channel lasts approximately 10 microseconds. The half period of the discharge in the explosion circuit is 12 microseconds in this case.

The photograph therefore confirms the assumed sequence with which the current channels are formed, and shows at the same time that these channels are formed and exist only in the first half period of the current.

3. ANALYSIS OF RESULTS

The experimental results given above shows that when electric explosion occurs in vacuum the wire vapors escape at high velocities in directions perpendicular to the wire surfaces. It is known that the explosion of ordinary explosive substances has analogous properties. The physical features of processes that develop in ordinary explosions have been sufficiently well studied at the present time. In view of the common basic properties that electric explosions have with ordinary explosions, the qualitative results given above can be understood from the existing theory of ordinary explosive processes, particularly if the explosion has cylindrical symmetry (see, for example, Ref. 6).

Unlike ordinary explosions, electric explosions are characterized by forces that result from a strong magnetic field due to the current. These forces, as was already noted in Ref. 4, cause certain anomalies of the electric explosion, such as periodic stratification of the escaping wire vapors and others, occurring as the joint result of the axial compression of the wire by thermal shock and a radial compression of the wire by the magnetic field of the current. Figures 2–5 confirm the ideas presented in that work concerning the mechanism of the electric explosion of the wire.

Let us analyze in greater detail the possible causes of the thin-layered cylindrical current channels formed by electric explosion of wires in a vacuum. Starting from the interpretation of the time exposures of the explosion as given above, and also of the mirror scanning of the explosion, one must assume that the main cause the current is concentrated in thin-layered channels is the radial motion of the wire vapors at high velocities in a strong magnetic field of the current.

The time exposures shows that prior to the explosion, the wire is surrounded by a thin layer of a strongly stringing and brightly glowing discharge. Let us assume that the radial thickness of this layer is zero and that the current is distributed uniformly over the cross section of the wire (i.e., we neglect the skin effect, a valid assumption for the dimensions of our wire). In this case the leading front of the vapor stream launched by the explosion must break through the magnetic field H of the current. Inside the wire we have

$$H = 2Ir/r_0^2, \quad (1)$$

where I is the total current in the wire, r_0 the wire radius and r the distance from the point of observation to the wire axis. Outside the wire we have

$$H = 2I/r. \quad (2)$$

In our experiments the current is of the order of 10^4 amperes and r of the order of 10^{-2} cm, making H approximately 10^5 oersteds on the surface of the wire.

A ballistic determination of the average escape velocity of the escape of the wire vapor yields approximately 10^5 cm/sec. Considering that in explosive evaporation in vacuum the velocity of the leading stream of particles is generally considerably higher than the average escape velocity of the explosion products,[6] we can assume the escape velocity of the vapor to be even higher at the beginning of the explosion.

The stream moving through the magnetic field must produce electric field (see Ref. 7, for example) determined from the vector product

$$\mathbf{E} = (1/c)\,[\mathbf{vH}], \tag{3}$$

where c is the velocity of light, **v** the velocity of the vapor stream, and H the magnetic field intensity. When the vapors scatter radically this field has the same as the external field E_k. We thus have an effective total field $E_k + E$ outside the wire, while inside the wire, where $\mathbf{v} = 0$ and consequently $E = 0$, the field intensity is only E_k. For the order of magnitude of v and H in our experiments, we have from (3) a field E of 1,000 v/cm on the surface of the wire. An additional field E formed where the vapor streams move should accelerate the ignition of the arc discharge along the wire and correspondingly decrease the discharge resistance. To illustrate this process, Fig. 12 shows the oscillogram of the current produced during an explosion of a wire in vacuum. It is evident from this oscillogram that the current in the wire first increases smoothly until it reaches a "plateau" of 1.2×10^4 a (in the explosion circuit) approximately two microseconds after the start of the discharge. The width of the "plateau" is approximately 0.3 microseconds. Within the "plateau" region the discharge resistance becomes sufficient to carry the remaining capacitor voltage and the current stops increasing. The firing of the arc and the sharp reduction in the resistance at the end of the discharge "plateau" causes the current to resume its increase.

According to Eq. (2), the magnetic field on the surface of the wire reaches a value of approximately 3×10^5 oersteds in the "plateau" region. The formation of such a large magnetic field leads to a strong stringing of the discharge.[7] This gives rise to the first current channel, described above in the discussion of the wire-explosion time exposures. At this stage of the discharge, the total current flow should divide between the wire and the first channel according to the ratio of their resistances.

The first current channel can remain stable at the surface of the wire as long as the pressure from the side of the radial vapor stream against the strung discharge layer does not exceed the counterpressure due to the magnetic field of the total current. In view of the high discharge power, particularly in the "plateau" stage, a pressure excess is bound to occur and initiate a rapid radial broadening of the channel.

The broadening of the channel forms first of all an arc discharge along the wire and reduces correspondingly the applied field E_k from several thousands v/cm in the "plateau" stage to several v/cm in the arc. This should result in a certain redistribution of the current in the discharge gap, owing to the effect of the radial motion of the wire vapor and of the magnetic field on the distribution of the field E. The current is guided along the channel axis only by the weak field E_k, for H and v are equal to zero here and hence $E = 0$ from (3). Towards the outer boundary of the channel we have [from Eq. (1)] that H increases in proportion to the radius (it is assumed that in this stage the current is distributed approximately uniformly over the cross section of the channel), reaches a very sharp maximum on the outer boundary of the channel, and then starts diminishing in inverse proportion to the radius, in accordance with Eq. (2). The dependence of the stream velocity v on the radius can be given here only qualitatively. At the start of the explosion the velocity on the surface of the wire increases almost in a jump to a certain critical value, beyond which it does not experience any considerable variation.[6] In view of the fact that the metal vapor shows good condensation properties, the same distribution should be maintained from there on.

Based on the above-mentioned distributions of v and H, Eq. (3) shows that the distribution of the field E will be characterized by a sharp maximum at the outer boundary of the current channel. From the values of H and v given above it follows that the value of this maximum is considerably greater than the value of E_k in the arc, and almost the entire discharge current should therefore be concentrated in the narrow region around the maximum of the field E.

As the current channel expands the current density in its conducting layer diminishes to agree with the accompanying decrease in H and E. The concentration of the particles in the radial streams which penetrate the thin walls of the channel also decreases. The walls of the channel therefore become continuously more "transparent" to these streams, and at a certain distance from the wire axis a new equilibrium is established between the forces accelerating the channel and the pressure of the magnetic field which retards its radial expansion. This makes possible the stabilized state corresponding to the second current channel. In view of the cylindrical symmetry of the magnetic field and of the radial vapor streams, these channels should be coaxial with the wire.

The duration of the stabilized channel should depend on the time interval during which E remains sufficiently high in the thin conducting layer of the channel. From Eq. (3), this should be determined in turn by the character of the time dependence of H and v. We do not know tht time dependence of v, but it follows from the current oscillogram on Fig. 12 that H can stay sufficiently high for a considerable fraction of the first half cycle of the current. Assuming that v also remains sufficiently high during the same time, one can say that the duration of the stabilized state of the second channel cannot exceed the first half cycle of current.

Once the discharge current passes through zero at the end of the first half cycle, the second current channel cannot form again since the conditions necessary for its formation no longer exist (no stringing of the current and no high-velocity radial vapor stream). This is in good agreement with the mirror-scanned picture of the wire explosion in vacuum given above.

It follows also from the above qualitative mechanism for the formation of current channel that the greater the initial voltage on the capacitor, i.e., the greater the radial velocities and the concentration of particles in the vapor stream, and also the greater the current density in the corresponding channels, the greater the diameter of the stable channel should be. It is also easier to understand the variation in channel diameter and of its glow intensity with the disturbances produced by the radial vapor streams and of the re-distribution of the current in the discharge gap (Figs. 8 and 9). These changes are related to the corresponding changes in the radial velocity of the vapor streams and of the magnetic field. The broadening of the second current channel near the discharge electrodes (Fig. 6 and 7) is due to the fact that the electrode streamsers, by compressing the radial flow axially, cause it to become radially accelerated to some extent.

The above discussion makes it possible to understand the principal features of the processes that lead to the formation of the first and second current channels in electric explosion of wires in a vacuum. It is evident, however, that the picture given above is merely a rough approximation of actuality and cannot pretend to offer any complete description of the phenomena observed. For example, it is still not understood why third current channels are produced at high capacitor voltages, etc. A more complete analysis of the observed phenomena should evidently be based on a quantitative theory of magnetic-hydrodynamic discharges in a moving gas stream.

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