ELECTRIC EXPLOSION OF SPIRAL WIRES IN VACUUM

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When a bent wire is exploded in vacuo, the motion of the explosion products through the magnetic field of the current produces current tubes and also certain glow effects, due to the interaction of the streams of explosion products with each other. By scanning the explosion with a mirror, the stream fronts were found to have a speed of 10^6 cm/sec. A possibility of thermally insulating the plasma by means of the strong magnetic field that exists during a very short time of explosion is demonstrated. A qualitative explanation is proposed for the observed effect.

1. INTRODUCTION

THE authors[1] have previously reported on an experimental investigation of electric explosion of wires in vacuo. An examination of these data has led to the conclusion that in the case of straight wires the radial motion of the explosion products through the magnetic fields produces thin layered cylindrical channels, coaxial with the wire, through which most of the discharge current flows. To investigate this effect further, we experimented with electric explosions of wires curved in different manners (mostly in helical form).

In the investigations we used integral photography of the explosion, continuous photography of mirror scans and oscillography of the current and voltage, the setup being approximately as described in reference 2.

A capacitor bank with total capacity of 4.8 μf at 50 kv working voltage was used to explode the wires.

2. RESULTS OF THE EXPERIMENTS

Figures 1 and 2 show photographs of the explosion curves of copper wires in vacuo. Photograph 1 of Fig. 1 shows the characteristic explosion picture of helically-wound wires at relatively high explosion-circuit capacitor voltages. The photograph was taken at right angle to the axis of the helix. As in the case of all integral photographs of explosions, this picture shows the glowing wire at the initial stage of the discharge, during which it acquires the energy needed for the explosion. The glow of the wires is due to the presence of a thin brightly-glowing discharge layer, becoming coiled under the influence of the strong magnetic field of the current.[1] An examination of the current and voltage oscillograms shows that the explosion of the wire occurs at the end of this stage and the discharge is immediately followed by a second discharge in the vapor of the wire. The remaining portion of the picture, which obviously occurs after the start of the explosion of the wire, must be attributed to mutual collisions between the streams of explosion products and to their motion through the magnetic field of the current.

The mechanism of interaction between the moving explosion products and the magnetic field, with which we begin our examination of the results presented here, is described in detail in reference 1. It is based on the following two premises:

1. Regardless of the initial shape of the wire, the explosion products propagate in its immediate vicinity perpendicularly to the wire surface.
2. When the explosion products travel through the magnetic field **H** with a velocity **v**, an additional electric field $\mathbf{E} = (1/c)\mathbf{v} \times \mathbf{H}$ (c is the velocity of light in vacuo)[3] is produced in the discharge and causes a corresponding redistribution of the current density.

The first premise makes it easy to explain the inclined glowing strips of photograph 1, located midway between each pair of neighboring turns of the helix and parallel to the latter. Actually, when the streams move in directions normal to the wire, the only streams colliding are those beginning on sections of neighboring turns, which lie on one plane normal to the turns. If the rates of flow are equal, the streams will meet at points in space located on this plane and equidistant from the above mentioned cross sections. At different points of space, the collisions will occur at different angles and at different instants of time, depending on the positions of these points relative to the wire. At points opposite the streams, in view of the short duration of the processes (see

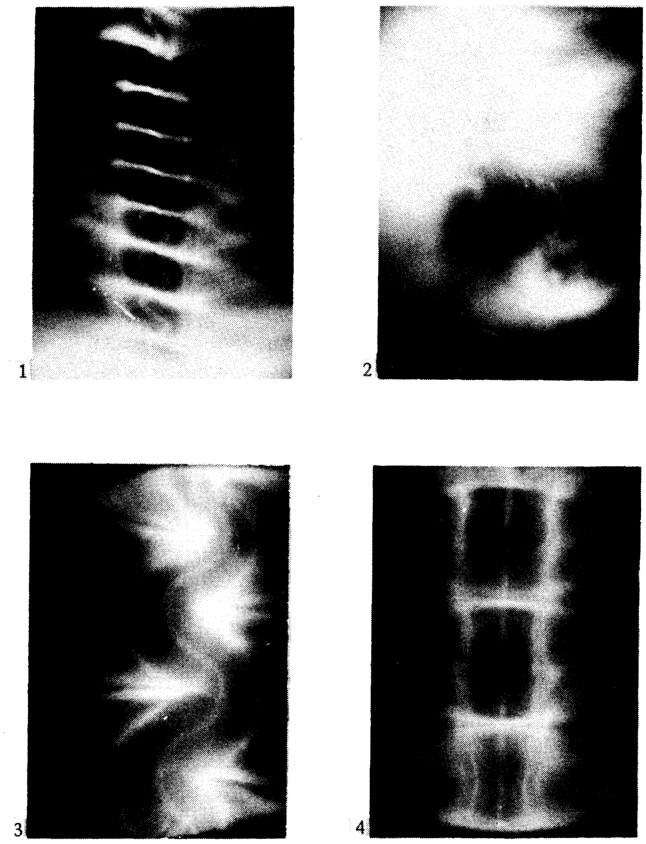

FIG. 1. Integral pictures of the explosion of copper wires: 1) helix of 3 mm diameter and 4 mm pitch, made of wire 0.15 mm in diameter and 80 mm long. Initial voltage on explosion-circuit capacitor $U_0 = 30$ kv; 2) helix of 8 mm diameter and 8 mm pitch, made of wire 0.2 mm diameter and 80 mm long, $U_0 = 30$ kv; 3) sinusoidal wire of 0.2 mm diameter and 70 mm length. $U_0 = 30$ kv; 4) the same picture in a different projection.

below), adiabatic compression will occur and produce a corresponding glow of the vapors. The bright strips represent the summary picture of all these glows. In the case of a cylindrical helix, the geometric locus of points with maximum glow intensity will be a helical surface having a common axis with the helix and passing midway between each pair of neighboring turns. For a given stream velocity, the visible radial extent of this surface should be limited by the fact that as the distance from the axis of the helix increases, the streams intersect at smaller angles and their density diminishes at the same time. The resultant reduced compression causes the glow of the vapor to cease at a certain distance from the axis of the helix. It is seen from this picture, however, that even before this takes place, the strongly compressed radial streams begin to branch axially, and it is there that the boundary of the glowing helical surface is located. As the helix is gradually stretched, the interaction between these streams becomes weaker, and the explosion takes on the appearance of that of a straight wire.[1]

It must be noted that the photographs of the explosion of a helix show one half of the glowing helical surface, that closest to the camera lens, since the light from the opposite half is fully screened by the explosion products that propagate in the direction of the lens. This is confirmed by photograph 2 of Fig. 1, taken at 45° to the axis of the helix, on which we see only the glow of the original helix. The image of the glowing helical surface is completely lacking here, since the glow of the explosion products is screened by the radial streams that move between neighboring portions of the helical surface. In the foreground of the picture we see a glowing plasma flowing along the axis of the spiral. This plasma is produced by the radial compression of the vapor inside the spiral.

Thus, part of the picture of the explosion of a helical wire can be adequately explained by the interaction between the streams of explosion products.

Photograph 1 and the other analogous photographs show an almost cylindrical glowing thin layer, coaxial with the helix and intersecting in sequence all the neighboring portions of the heli-

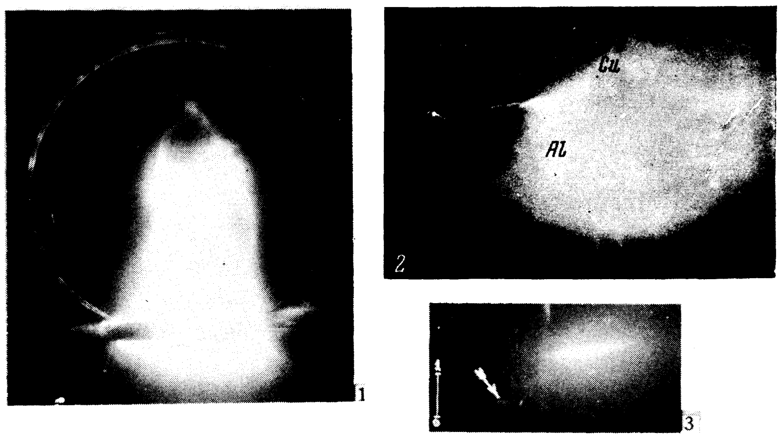

FIG. 2. Pictures of explosions of wires: 1) wire bent in circle of 50 mm diameter, wire of 0.2 mm diameter and 120 mm length, $U_0 = 30$ kv; 2) straight wires of aluminum and copper, joined at an angle of 45°, each wire 25 mm long, 0.15 mm in diameter, $U_0 = 30$ kv; 3) mirror scan of explosion of wire bent in circle of 25 mm diameter, wire of 0.2 mm diameter and 40 mm length, mirror speed ~60,000 rpm, $U_0 = 30$ kv.

cal surface. The glow of this layer cannot be attributed to the interaction between the streams, for in these regions all the streams propagate mostly in the radial direction without any noticeable mutual interference. According to reference 1, the glow of a thin-wall cylinder can be attributed to the formation of suitable current channels (which we shall call current tubes), provided the magnetic field due to the current has a suitable configuration.

Let us trace the possible variations in the form of the current-induced magnetic field during the explosion of the helix. In the first stage, when the wire acquires the energy for the explosion, the current obviously retains its helical form, and the field inside the helix is determined by the number of ampere turns. After the start of the explosion, the streams move inside the helix transverse to this field and, according to the second premise, produce an additional electric field, which keeps the current helical until the encounter with the streams from the neighboring turns causes a breakdown between the streams, thus "straightening" the current. From this instant on the outward-directed streams from the helix penetrate the magnetic field due to the straight current. As a result, according to the mechanism indicated in reference 1, it is possible for a current tube to form.

Photograph 3 of Fig. 1 shows the explosion of a wire bent in sinusoidal form, photographed perpendicular to the plane of the wire. Photograph 4 of the same figure shows the explosion of a similar wire photographed parallel to this plane. Each of these photographs shows the glowing wire. Photograph 3 shows that the streams from each half wave of the sinusoidal wire converge to corresponding "foci" where adiabatic compression causes the vapor to glow bright. Upon leaving the region of maximum compression each stream clearly breaks up into two streams, which diverge in the direction of the axis of the sine wave. Sometimes the streams split into three parts, the central one remaining perpendicular to the axis of the sine wave. The same photograph shows the current tube, which has, in the projection used here, the same type of curvature as the wire, in accordance with the distribution of the streams and of the magnetic field due to the current. It must be noted that in this case, too, the current tube is better delineated in places where the stream flow is undisturbed. Photograph 4 shows all these phenomena in another projection.

Photograph 1 of Fig. 2 shows the explosion of a wire bent into a circle, taken perpendicular to the plane of the circle. In this case the radial streams that move in the plane of the circle or make small angles with this plane collide with each other at the center or near the center of the circle, causing adiabatic compression and glow of the vapor. What is remarkable here is the absence of a current tube around the wire. This is due to the small gap between the ends of the wire (~ 10 mm), which breaks down within a very short time ($\sim 0.5\ \mu$ sec) after the start of the discharge, so that the current stops flowing along the original position of the wire. We thus have here a positive confirmation of the direct connection between the glow of the tubes and the flow of the discharge current through the tubes. This experiment shows also that the glow of the vapor at the place where the streams converge is due to adiabatic compression and not to the current.

If wires bent in zigzag shape are exploded, the geometric loci of the points of convergence of the streams, in accordance with the first premise, should be planes perpendicular to the plane of the wire and passing through the corresponding zigzag vertices. The photographs show the projections of these glowing planes in the form of straight lines, coinciding with the diagonals of the corresponding zigzag angles, if the speeds of the streams are the same. If the zigzag angle is made up of wires of different material, say aluminum and copper, then, as can be seen from photograph 2 of Fig. 2, the projection of the glowing plane is nearer to the copper wire. This means that under identical explosion conditions, the explosion products of aluminum propagate faster than those of copper.

Photograph 3 of Fig. 2 shows a mirror scan of the explosion of a wire bent in a circle. The slit of the optical system was aligned with the vertical diameter of the circle. The scanning photograph shows first the image of a glowing wire (marked by an arrow) and then, following the explosion of the wire and the convergence of the stream to the center, the corresponding glow of the condensed vapor. Knowing the radius of the circle and the scanning rate, it is possible to calculate from this picture the velocity of the fronts of the explosion-product streams. Calculation yields a value of $\sim 10^6$ cm/sec. It is also seen from this photograph that the duration of the glow of the wire prior to the start of the explosion is $\sim 0.3\ \mu$ sec, and the glow of the vapor compressed at the center of the circle lasts $\sim 5\ \mu$ sec. Obviously, the scattering of the explosion products terminates within this time.

Figure 3 shows by way of an example an os-

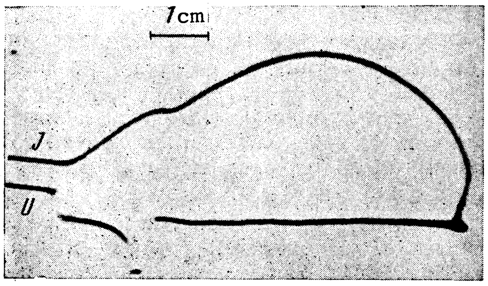

FIG. 3. Oscillogram of explosion of copper helix of 10 mm diameter and 10 mm pitch, wire of 0.2 mm diameter and 150 mm length, $U_0 = 10$ kv.

cillogram of the discharge, obtained during the explosion of a helical wire in vacuum. The current oscillogram (upper line) shows the characteristic "plateau" of the current, due to the fact that during this stage all the residual voltage across the capacitor is applied to the wire, and the current does not increase.[1] The voltage oscillogram (lower curve) confirms this fact. From similar oscillograms it is possible to calculate with sufficient accuracy the energy balance in the wire-explosion process.[4] Such calculations show that at relatively high capacitor voltages, the wire receives, during the time from the start of the discharge to the end of the "plateau" of the current, an energy equal to or perhaps greater than the total energy of evaporation.

3. DISCUSSION OF RESULTS. COMPARISON WITH RESULTS OF OTHER INVESTIGATIONS

The photographs discussed above demonstrate clearly the spatial distribution of the streams of the explosion products of the wires and indicate that the interactions between these streams exhibit certain peculiarities. For example, it turns out that in certain cases, after adiabatic compression, the streams are capable of branching into several independent streams. An explanation for this branching must be sought in the short duration of the compresssion process and in the high degree of this compression. From an examination of photograph 3 of Fig. 2 it follows that the duration of the compression process does not exceed several microseconds and since the velocity of the front of the streams reaches $\sim 10^6$ cm/sec, the degree of compression should be high.* From an examination of the integral explosion pictures it follows that the necessary condition for the branching of the streams is that the streams reach a region in space where the angle of convergence of the neighboring streams diminishes rapidly and where, at the same time, the stream density diminishes. As a result, conditions are produced for an almost explosive expansion of the previously compressed streams. The pictures cited show that the expansion is mostly in the direction of the symmetry axis of the wire. Consequently, this is the very direction in which the component parts of the stream effect the momentum exchange necessary for the branching. It can be assumed that the cause of the observed branching of the streams is the same factor that leads, in the case of a strong explosion with spherical or cylindrical symmetry, to the formation of regions of reduced density and pressure at the center or along the axis of the explosion (see, for example, reference 5).

When we recorded the results of the experiments, we became convinced that the occurrence of current tubes of different shapes can be qualitatively explained on the basis of the mechanism cited in reference 1. This again confirms the correctness of the aforementioned second premise.

The effect of the motion of the medium on the spatial distribution of the discharge-current density was also considered in references 6 to 8 in connection with an investigation of the compression of a plasma column (at low gas pressures) under the influence of a magnetic field due to a very intense pulsed current. There the plasma column has a chance to negotiate several transverse compressions and expansions. The added electric field produced during the compression is directed opposite to the external field, and in those regions of the plasma where the radial speed of the medium is maximum, it may even lead to reversal of the current.

In the explosion of wires, in view of the good condensibility of the metal vapor, the explosion-product streams are always directed away from the wire towards the cold walls of the chamber. The additional electric field in the regions of the radial stream motion has therefore the same direction as the external field. This indeed makes stable current tubes possible.

The mirror scan of the explosion shown in photograph 3 of Fig. 2 makes it possible to estimate with greater accuracy, than in reference 1, the connection between the duration of the scattering of the explosion products and the lifetime of the current tubes. According to this photograph, the scattering of the explosion products terminates after several (5 or 6) microseconds. Since, in accordance with our assumption, the existence of the current tubes is directly connected with the

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*A picture of the explosion of a copper helix connected in series with a tungsten wire shows that the glow of the compressed vapor is considerably brighter than the surface glow of molten tungsten.

presence of corresponding radial streams, it is obvious that with the cessation of these streams the current tubes should also vanish. Thus, the lifetime of the current tubes for wires of usual dimensions (length ~ 10 cm, diameter ~ 0.1 to 0.2 mm) should not exceed several microseconds. This is well confirmed by the mirror scan of the explosion of both direct and curved wires.

Certain data obtained during the explosion of wires in vacuo indicate apparently the existence of magnetic thermal insulation of the plasma during the stage of strong coiling of the discharge on the surface of the wire. In fact, many mirror-scan explosion pictures show that at relatively high discharge-capacitor voltages and at the usual wire dimensions, the duration of the strong discharge-coiling stage amounts to 0.3 sec. Comparison of the integral glow of the coiled discharge with the integral glow of the surface of molten tungsten wire (see reference 3) shows that the discharge glow is considerably brighter than the tungsten. Considering that the duration of the tungsten glow is at least one order of magnitude greater than the duration of the glow of the coiled discharge, we can conclude that the degree of ionization of the plasma in the coil should be higher. This is quite natural, for according to discharge oscillograms taken of coils of transverse dimension on the order of the radius of the wire (see integral photographs), the current density reaches $\sim 10^7$ amp/cm^2, and the field gradient reaches an order of 10^3 v/cm. In addition, calculation of the energy from the oscillograph data shows that in the cases considered here the energy supplied to the wire towards the end of the strong discharge-coiling stage is equal to or even greater than the total energy of evaporation. Under this condition, the wire would evaporate vigorously prior to the termination of the coiling stage and the integral photographs would not show a clear picture of the stabilized coil. Thus, the dense and highly-heated plasma turns out to be confined in the very narrow channel of the coil, which bounds with the high vacuum, showing unambiguously the existence of good magnetic thermal insulation for the plasma. This is readily understood if it is taken into account that according to the oscillographic data the magnetic field at the surface of the string reaches several times 10^5 Oe. The "magnetic wall" of the current channel can then withstand, from the plasma side, a maximum pressure of $\sim 10^4$ atmos, and the strong coiling of the current can exist until the thermal pressure of the plasma exceeds this value. As soon as the plasma pressure becomes greater, an explosive scattering of the vapor begins through the magnetic field of the current, and the effects described above take place.

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192