Experimental Study of Ionized Matter Projected across a Magnetic Field*

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A plasma gun has been developed which projects ionized matter (metallic and deuterium ions) at speeds up to 2×10^7 cm per second. There is some evidence to support the hypothesis that the plasma projected by this gun comes off in an expanding torus which is shaped by its own magnetic field. When the plasma gun is fired into a dc magnetic field, the plasma forms a compact geometrical configuration (a plasma-magnetic entity called a plasmoid) which proceeds across the magnetic field. Plasmoids appear to be plasma cylinders elongated in the direction of the magnetic field. Plasmoids possess a measurable magnetic moment, a measurable translational speed, a transverse electric field, and a measurable size. Plasmoids can interact with each other, seemingly by reflecting off one another. Their orbits can also be made to curve toward one another. Plasmoids can be made to spiral to a stop if projected into a gas at about 10^{-3} mm Hg pressure. Plasmoids can also be made to smash each other into fragments. There is some scant evidence to support the hypothesis that they undergo fission and possess spin.

PRODUCTION OF A PLASMOID IN FIELD-FREE SPACE

A BUTTON-TYPE source of plasma, delineated in Fig. 1, can be used to create and project a plasma, consisting of metallic (Ti) ions, and deuterium ions, and electrons, at speeds in the forward direction up to 2×10^7 cm/sec. The speed is measured by a time-of-flight measurement in a vacuum chamber. With this type of source the projecting mechanism is a high-current (1000 to 10 000 ampere) pulsed (0.1 to 0.5 μsec duration) arc produced in vacuum between the exposed ends of two metallic electrodes. The number of ions projected per pulse is in the range of 10^{15} to 10^{18}, depending upon the peak current and the pulse duration.

Evidence in the form of probe traces suggests that the plasma is emitted in a toroidal form, as postulated in detail in Fig. 2. A Kerr-cell, short-time exposure (0.5 μsec) taken of a source firing in the manner shown in Fig. 2, with a delay of 0.5 μsec, is shown in Fig. 3. This photograph, which displays the plasma in its own recombination light, further confirms our suspicions that the plasma is emitted not as an amorphous blob, but in the form of a torus as postulated in Fig. 2. We shall take the liberty of calling this toroidal structure a plasmoid,[1] a word which means plasma-magnetic entity.

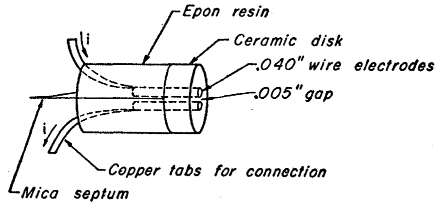


FIG. 1. A button-type, pulsed source of plasma.

* This research was performed under the suspices of the U. S. Atomic Energy Commission.

[1] The term "plasmon" (in line with the term "geon" used by Wheeler) was originally proposed. However, David Pines (of Princeton University) has pointed out that the term "plasmon" should be reserved for a quantum of plasma-oscillation energy. He kindly proposes the term "plasmoid," which we adopt.

The word plasmoid will be employed as a generic term for all plasma-magnetic entities.

It has been possible with a magnetic coupling loop to pick up signals which can be demonstrated to be associated with the magnetic fields trapped by the plasmoid of the type shown in Figs. 2 and 3. (Note that no external magnetic field is employed here.)

The type of plasmoid (to be designated as the π_1 plasmoid, because it is unstable) diagramed in Fig. 2 and photographed in Fig. 3, is shown in more detail in Fig. 4. In addition to the projected velocity, v, a small

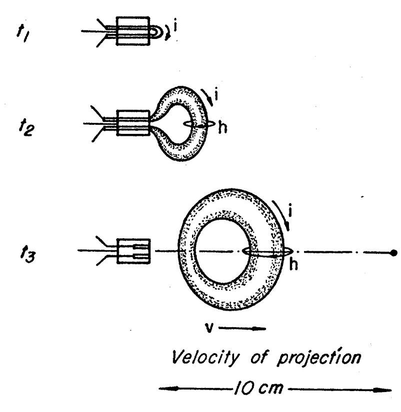


FIG. 2. Mechanism of projection of a plasmoid. No externally excited magnetic field is employed.

amount of spin mass-velocity v_m (carried predominantly by the positive ions) is to be expected because of the radial polarization current (along r) produced by the original pinching action of the high current. It is to be expected that the π_1 plasmoid will expand as time goes on, both in the directions of increasing R and r.

EFFECT OF FIRING A PLASMOID ACROSS A MAGNETIC FIELD

A rather surprising result occurs when the source of Fig. 1 is placed in vacuum ($\sim10^{-5}$ mm Hg) in an externally applied dc magnetic field and fired across the field. The plasma apparently has no difficulty in crossing the magnetic field, although probe measurements show that a magnetic field greater than about 500 gauss reduces the translational speed of the plasma by about a factor of $\frac{1}{2}$.

We have endeavored to determine by probes, photographs, and magnetic coupling loops the nature of the plasma density configurations and current configurations resulting from producing a plasmoid in a magnetic field. Photographs taken with a Kerr cell under the same circumstances as in Fig. 3, but with various magnetic fields applied, are shown in Fig. 5. These photographs were taken in an endeavor to delineate, if possible, the process of formation of a plasmoid in a magnetic field. Although the pictures in Figs. 3 and 5 were taken at a poor vacuum ($\sim 10^{-3}$ mm Hg) in order to slow the plasmoid down and thereby give more light for the photographs, they are nevertheless of some value in suggesting the process whereby the plasmoid is produced.

With the use of a pair of short (0.5 cm), small-diameter (0.1 cm) probes placed 10 cm in front of the source, it is possible to measure in the laboratory system the electric field $\mathbf{E} = -\mathbf{v}\times\mathbf{H}/c$, associated with the projection of plasma at a velocity $\mathbf{v}$ across the magnetic field $\mathbf{H}$. The probes were placed 0.5 cm apart (see Fig. 8) in the vertical direction, were oriented perpendicular to the plane of the paper (in Fig. 2), and the magnetic field was perpendicular to the plane of the paper (in Fig. 2). The type of signal received across a 50-ohm termination on the oscilloscope cable is illustrated in Fig. 6, where it can be seen that the sign of $\mathbf{E}$ changes as the magnetic field is reversed. With a measured signal of 25 volts across 0.5 cm there is a measured value of $|\mathbf{E}| \cong 50$ volts/cm. With a velocity $|\mathbf{v}| \cong 3\times 10^6$ cm/sec, as measured from the time of flight in the first trace of Fig. 6, and a value of $H=2000$ gauss, $|\mathbf{E}| = |-\mathbf{v}\times\mathbf{H}/c| = 60$ volts/cm. This agreement between measured and expected values is perhaps as good as can be expected within the precision of the experiment. The signals are likely to vary considerably from pulse to pulse depending upon how squarely the plasmoid hits the two probes and upon the speed of the plasmoid, which varies somewhat from pulse to pulse. Experimentally it is observed that a reduction in H by a factor of 2 reduces the measured value of E by approximately a factor of 2. Hence we can say that E is roughly proportional to H.

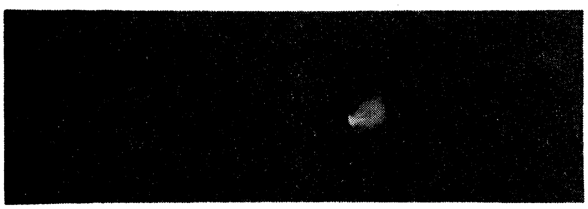


FIG. 3. Kerr-cell photograph, 0.5-μsec exposure, 0.5-μsec delay, of the profile of the luminous plasma ejected by firing a button source (see Fig. 1) at a peak current of 2000 amperes for approximately 0.2 μsec, with no external magnetic field applied. The actual length of the luminosity in the picture is 4 cm. A poor vacuum ($\sim 10^{-3}$ mm of Hg) slowed the plasmoid down somewhat and thereby rendered more light for the photograph.

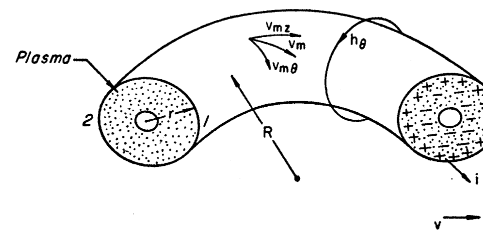


FIG. 4. Hypothetical detailed structure of the plasmoid of Figs. 2 and 3. This type of plasmoid will be called the π_1 plasmoid.

These traces shown in Fig. 6 indicate very clearly the *tight bunching* of the plasma *in the direction of propagation.* Indeed, it is typical that the plasma travels usually in two bunches instead of one. (The second bunch, visible at a later time, can be seen in Fig. 9.) Furthermore, there is evidence (see Fig. 7) derived from probes which indicates that the first bunch of plasma is actually distributed in the form of a shell. The probe traces of Fig. 7 are obtained with the arc current in a direction that produces a magnetic field which aids the dc magnetic field (in contradistinction to the current direction used for Fig. 6). Also, the peak currents in the source were greater for the traces of Fig. 7 than for those of Fig. 6. Under both of these circumstances for Fig. 7, the dimension of the plasma bunch in the direction of motion is greater than in the conditions used for

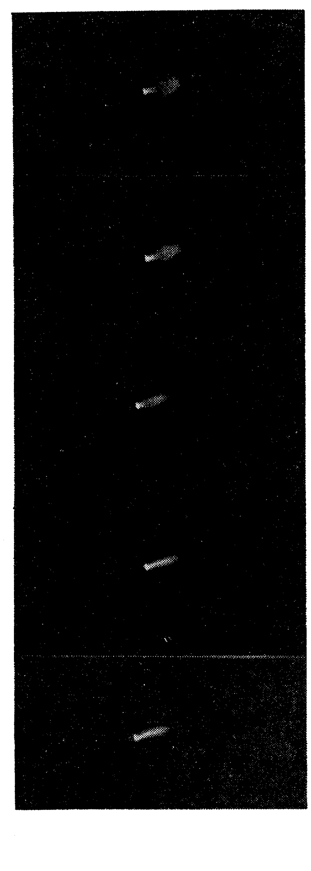


FIG. 5. Kerr-cell photographs taken under the same circumstances as Fig. 3, except that magnetic fields (geometry as shown in Fig. 2, with field out of paper) of values 600, 1200, 1800, 2400, and 3000 gauss have been applied. Note the squeezing effect in the vertical direction and the consequent tendency to form an elongated hairpin-like loop.

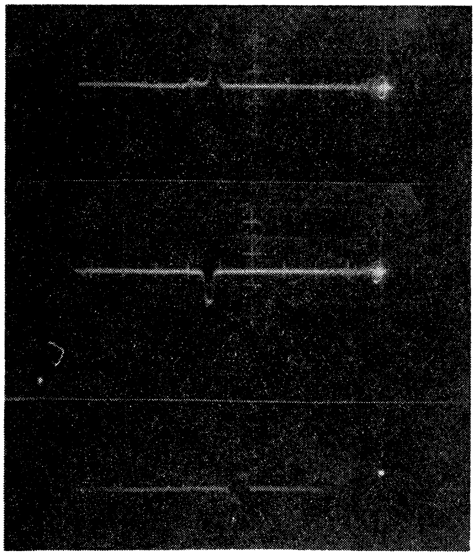


FIG. 6. The first two traces show signals measuring $\mathbf{E}=-\mathbf{v}\times\mathbf{H}/c$ picked up by two small probes 0.5 cm apart. The sweep speed is 0.5 μsec per cm, with time going from right to left. The peak current in the source is about 1800 amperes with a pulse duration of about 0.2 μsec. The first two traces are taken with sensitivities of 15 volts per cm and with magnetic fields (2000 gauss) in opposite directions. The third trace, taken with a sensitivity of 0.5 volts per cm shows the diamagnetic effect of a plasmoid as it passes a magnetic coupling loop 0.64 cm in diameter terminated in 50 ohms. The pulsed arc current in the source is in such a direction as to create a magnetic field which opposes the dc magnetic field for all the traces.

the traces in Fig. 6. The signals (corresponding to the first bunch of plasma) picked up by the two probes, 0.5 cm apart in Fig. 7, show the signal split into two peaks. This double structure suggests that the plasma bunch was large enough, and in a shell-like density configuration to give two peaks to the signal as the shell passed by the probes, in the manner diagrammed in Fig. 8.

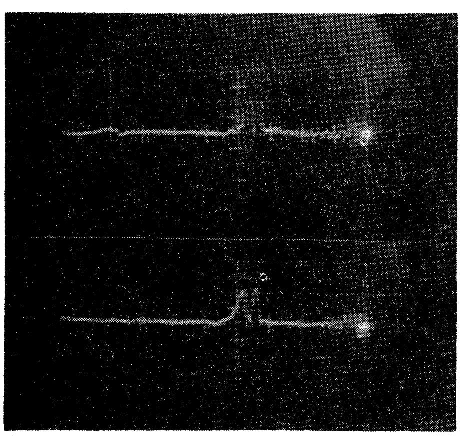


FIG. 7. Signals obtained with the same source and double probe configuration and same magnetic field (2000 gauss) as those in Fig. 6, except that the direction of arc current in the source has been reversed and increased to 3000 amperes. The sweep speed is 0.5 μsec/cm with time going from right to left. The sensitivity is 50 volts per cm for the first trace and 15 volts/cm for the second trace. The two peaks are believed to indicate a shell-like ion density distribution. It is typical that the plasmoids taken under the conditions of Fig. 7 travel faster than those of Fig. 6.

It is possible to take probe traces with only one probe (terminated to ground through 50 ohms). While the use of a single probe cannot give as accurate a measure of the electric field $\mathbf{E}=\mathbf{v}\times\mathbf{H}/c$, it can nevertheless be used as a rough measure of ion density in that no signal means (with almost absolute certainty) no plasma and finite signal means the presence of plasma. Traces from such a single probe are shown in Fig. 9, where the probe was moved in the y direction (see Fig. 8) so that both the first and second plasmoids emitted could be clearly located. Characteristically there are usually two plasmoids emitted regardless of the direction of current in the source or the orientation of the source in rotation about the x axis (see Figs. 2 and 8). The two-peak structure of the signal given by the first-arriving plasmoid in Fig. 9 is further suggestive that the ion density

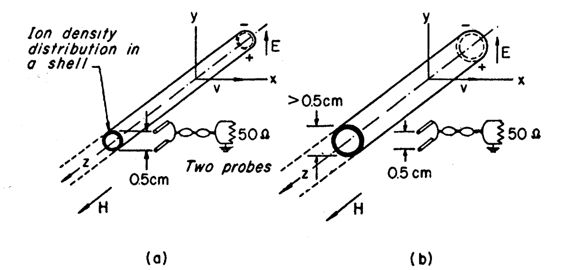


FIG. 8. Suggested shape of plasmoid with shell-like ion density distribution in motion with a velocity v across a magnetic field H. (a) represents the smaller diameter plasmoid (Fig. 6) which results from the pulsed arc current in the source creating a magnetic field that opposes the dc magnetic field. (b) represents the larger diameter plasmoid (Fig. 7) resulting from the source current aiding the dc magnetic field. It can be seen that in case a the probes will touch the plasmoid only once, but in case (b) the probes will touch twice.

distribution is in the form of a shell, as indicated in Fig. 8. An attempt at explaining the fact that plasmoids come in pairs will be given later.

A measurement of the diamagnetic signal imparted to a coupling loop with a dc magnetic field of 2000 gauss is shown in the third trace of Fig. 6. This signal, obtained at a distance of 10 cm from the source at the proper elapsed time for the plasmoid to travel from source to detector, has the proper duration and represents a magnetic field decrease within the center of the plasmoid of 30 gauss. This diamagnetic effect may possibly be much greater near the source. However, the technique of making these magnetic measurements is still so poor that the spurious pickup involved in the source current may swamp the desired signal if the detecting loop is moved close to the source. In order to get a true value of the diamagnetic effect of the plasmoid, its diameter must be known and it must strike the loop more or less on center. Variations in these conditions lead to great variations in the size and character of

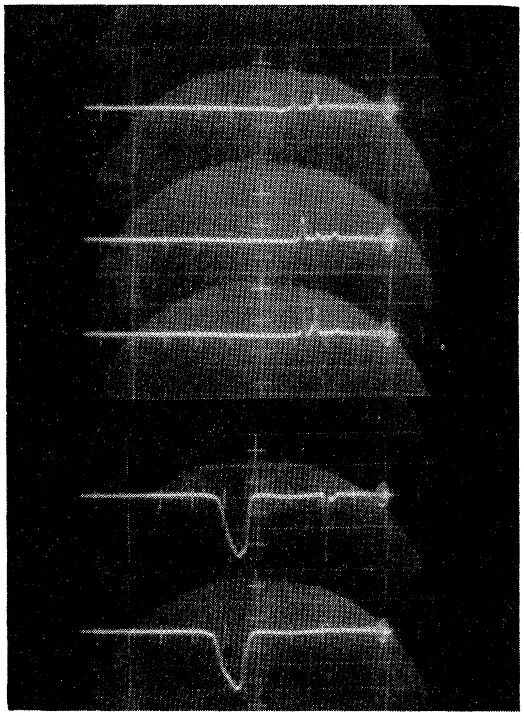


FIG. 9. Probe traces taken at a distance 10 cm from the source with a single probe which can be moved in the y direction to intercept either or perhaps both of the two plasmoids that are emitted and follow slightly different trajectories. The sensitivity is 5 volts/cm and the sweep speed is 1.0 μsec/cm. Traces 1, 2, 3 represent the probe on the x axis. Traces 4 and 5 represent the probe displaced 3 cm in the y direction. The dc magnetic field is 2000 gauss. The pulse current of 3000 amperes in the source produces a magnetic field that opposes the dc magnetic field.

signals from pulse to pulse. Hence, it is difficult to get a reliable quantitative measure of the diamagnetic effect. We look forward to improvements in the technique of these diamagnetic measurements. The maximum diamagnetic signal obtainable thus far at a distance of 10 cm from the source in a dc magnetic field of 2000 gauss corresponds to a magnetic perturbation of 100 gauss.

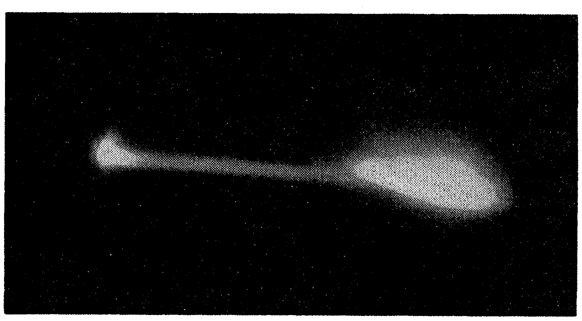


FIG. 10. Time-exposure photograph of trajectory of a plasmoid projected across a magnetic field of 1400 gauss. The electrodes of the source are oriented as shown in Fig. 2. The arc current of 3000 amperes is directed so that its magnetic field within its loop opposes the dc magnetic field. Note the two parallel lines of illumination with a dark septum in between.

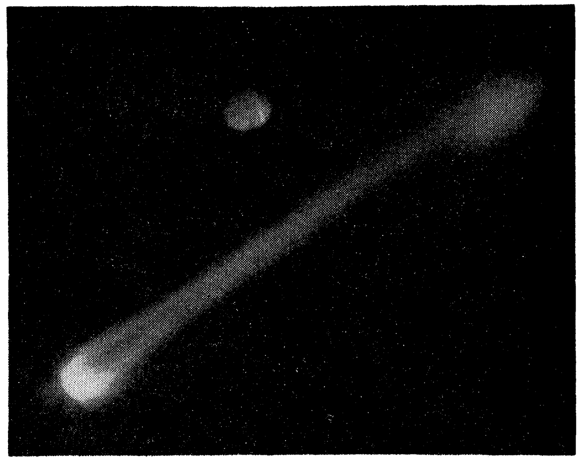


FIG. 11. Same as Fig. 10 except that the source arc current is reversed and the magnetic field is 4000 gauss. Note the wider spread between the lines.

INTEGRATED TIME-EXPOSURE PHOTOGRAPHS

Photographs of plasmoids, made by pointing a Land Camera along the magnetic field and focusing it at the location of the source, show the trajectories of plasmoids (luminous because of recombination light) as the plasmoids are projected across the magnetic field. These trajectories corroborate, to a certain extent, some of the conclusions drawn from the probe measurements: First, the trajectories show (for example, Figs. 10, 11, and 12) that the plasmoid is easily projected across the magnetic field. Second, pictures taken of the illumination produced when the plasmoid hits the opposite wall of the vacuum chamber indicate that the plasmoid is stretched out in a cylinder in the direction of H, as shown in Fig. 8. Probe measurements also show that the plasmoid is extended more or less like a straight cylinder in the direction of the magnetic field (as indicated in Fig. 8). Third, the study of many photographs indicates that there usually are two plasmoids formed and that the photographed illumination coming from each trajectory seems to be in two parallel lines. While it has been difficult to produce a clear-cut demonstration of the production of plasmoids in pairs by showing one or two photographs, Figs. 10 and 11 nevertheless show the characteristic double-line trajectory

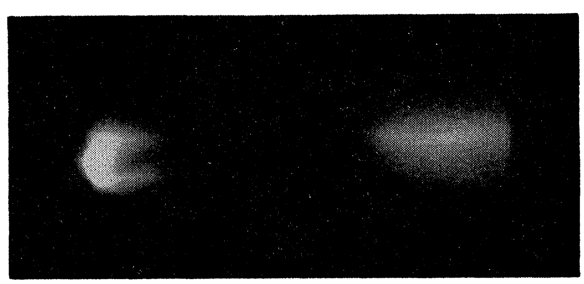


FIG. 12. Same as Fig. 10, except that the source electrodes are oriented so that initially the arc current is parallel to the magnetic field (see Fig. 14).

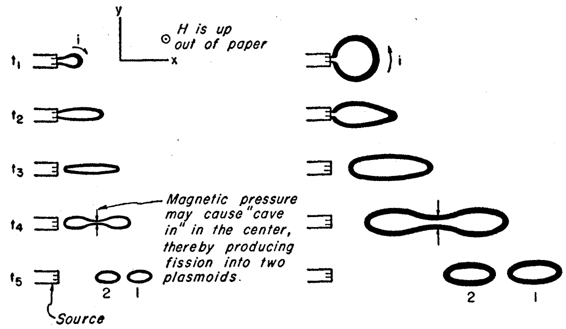


FIG. 13. A hypothesis concerning the way in which two plasmoids may be formed from the hairpin loop configuration observed in Fig. 5. The instants t_1, $t_2 \cdots t_5$ represent successive moments at which the plasmoid might be observed. The arc current flowing through the electrodes is assumed to have ceased between t_1 and t_2. End No. 1 may be expected to pick up most of the forward impulse, and hence it is to be expected that the plasmoid will stretch and perhaps snap in two as shown. Unfortunately the status of present techniques has not yet permitted the photographic examination of these later time intervals in detail. As time goes on the plasmoid will, of course, lengthen in the z direction (see Fig. 8).

which might be suggestive of the signature of a moving luminous cylindrical shell. However, Kerr-cell measurements show that the double-line tract emits illumination for several microseconds after the plasmoid has passed by. The double-line track, then, must be due to ions and electrons on the lateral periphery of the plasmoid. These ions and electrons did not have the full benefit of the polarization electric field (see Fig. 20) and therefore were left behind to recombine in the magnetic field. The luminous trajectory is then a kind of track formed by ionic debris left in the wake of the plasmoid.

Our techniques have not yet yielded a complete snapshot history of the formation of a pair of plasmoids. However, the Kerr-cell photographs shown in Figs. 2 and 5 and the time-integrated trajectories shown in Figs. 10 and 11 suggest that the modus of formation of the pair of plasmoids characteristically observed by

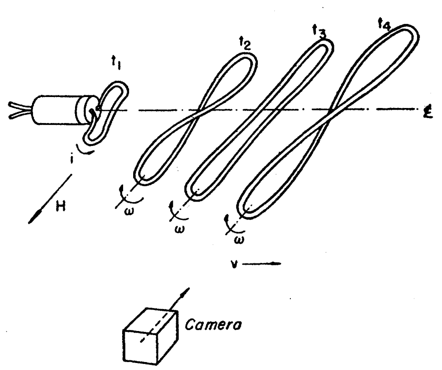
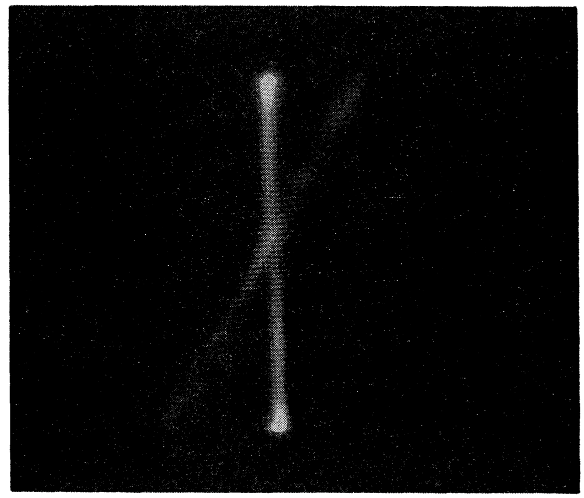


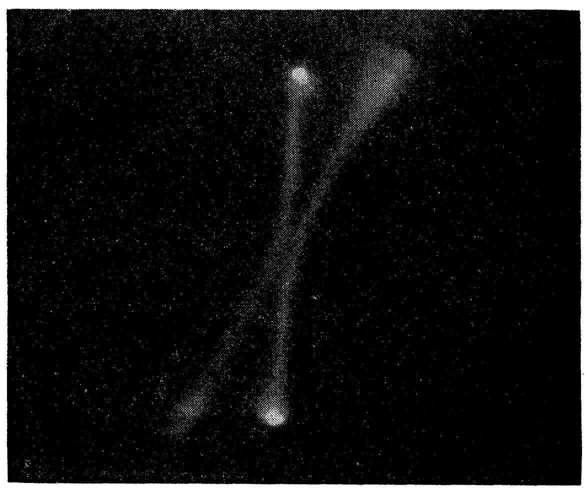
FIG. 14. Suggested plasma configuration which could explain the time-exposure photograph of the trajectory of plasma shown in Fig. 12. The camera is focused on the center line. A mechanical rotation ω of the configuration as the configuration is translated across the field with a velocity v can presumably give the time-exposure photograph shown in Fig. 12.

probes (see, e.g., Fig. 9) is something like that diagramed in Fig. 13.

The shape of the plasmoids projected with the source orientation used in the photograph of Fig. 12 has not yet been photographed with a short time exposure with the Kerr cell. However, the time-exposure picture of Fig. 12 suggests that the plasma configuration is that shown in Fig. 14. The camera is focused at the center-



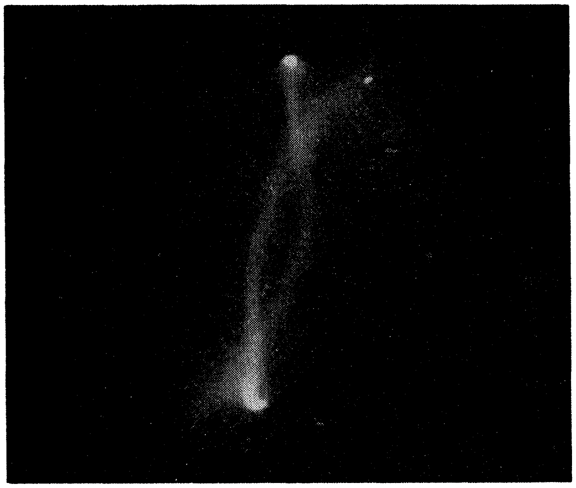
(a)



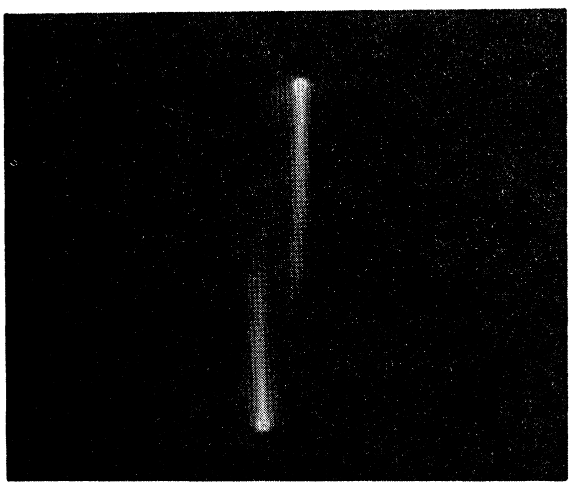
(b)

FIG. 15. Trajectories of plasmoids fired simultaneously at one another across a magnetic field at a pressure of 10^{-5} mm Hg with a separation distance of 10 cm. (a) $H = 2000$ gauss, peak current is 1500 amperes, the impact parameter is small. (b) $H = 4000$ gauss, peak current is 2700 amperes, the impact parameter is larger than in (a).

line in Fig. 14, and hence it is assumed that the two crossed-over trajectories correspond to the two limbs of the elongated torus as it rotates while moving to the right. The crossover point of the two luminous trajectories photographed in Fig. 12 is moved nearer the source as the magnetic field is increased. If the hypothesis set forth in Fig. 14 is correct, it could be concluded



(a)



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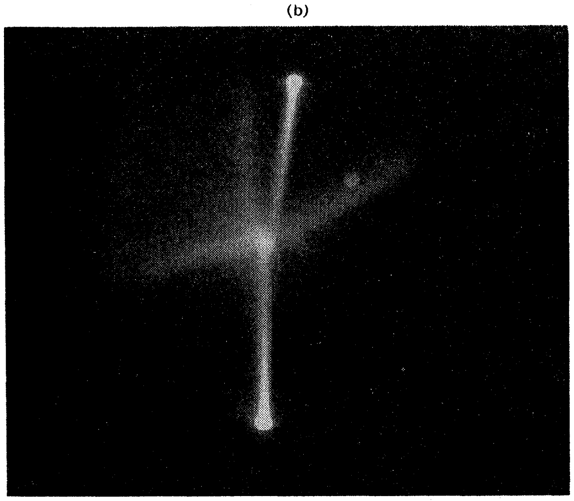


(c)

FIG. 16. Trajectories of plasmoids fired simultaneously at one another across a magnetic field at a pressure of 10^{-5} mm of Hg with a separation distance of 10 cm. The impact parameter has been changed in sign compared with Fig. 15. (a) $H=4000$ gauss, peak current is 2700 amperes. (b) $H=2000$ gauss, peak current is 1500 amperes. (c) $H=4000$ gauss, peak current is 2700 amperes. Here the plasmoids collide and break into fragments.

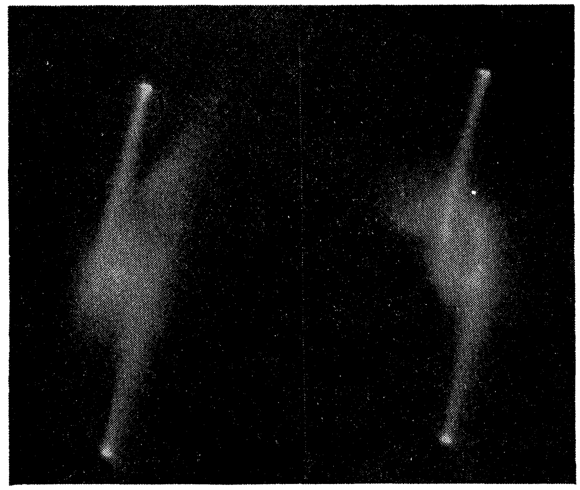


FIG. 17. Two plasmoids fired at one another across a magnetic field (into picture) of 4000 gauss at a pressure of 2.5×10^{-3} mm of Hg. The peak current in the source is 2700 amperes.

that the rotational speed ω increases with increasing dc magnetic field.

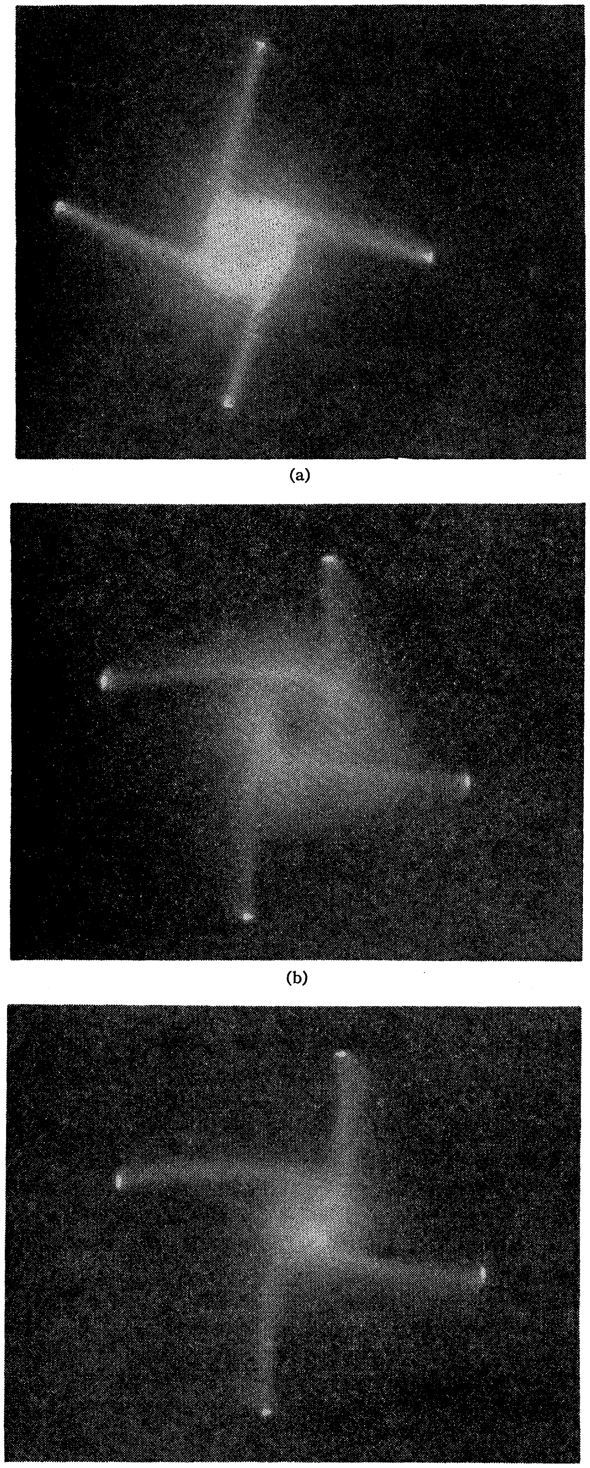
INTERACTION OF PLASMOIDS WITH ONE ANOTHER

Rather interesting and unexpected effects are produced when two plasmoids are projected at one another across a magnetic field. For example, the photograph, Fig. 15(a), of the trajectories of two plasmoids shows an interaction that looks (at first sight) like an elastic collision of two billiard balls in the center-of-mass system. Figure 15(b) shows another such interaction with a larger impact parameter, and Fig. 16 shows the results of the same experimental setup with the impact parameter changed in sign (i.e., the plasmoids pass on the left instead of on the right). More striking effects (see Fig. 17) can be obtained when two plasmoids are fired at one another when the pressure in the vacuum chamber is raised to about 10^{-3} mm of Hg. These effects become even more spectacular when four sources, instead of two, are employed (e.g., Fig. 18).

A photograph of the same process displayed in Fig. 18, but taken in the light of H_α through the use of a filter is shown in Fig. 19. A spectrogram taken of the light coming from the process photographed in Fig. 19 shows that the only lines in the spectrogram are those of Ti, Ti^+, and H (i.e., D). The residual gas in the vacuum chamber was presumably a combination of air and deuterium. There may have been some pump-oil vapor, although the system was trapped with liquid nitrogen.

EXPLANATION OF INTERACTION EFFECTS OF PLASMOIDS

In spite of the fact that there has recently been considerable theoretical interest in the interaction of plasmas and magnetic fields, there had been no theoretical predictions concerning the existence of plasmoids and such effects as the deflected trajectories shown in



(a) (b) (c)

FIG. 18. Trajectories of four plasmoids fired simultaneously across a magnetic field of 4000 gauss. (a) Peak current is 2500 amperes, pressure is 2.5×10^{-3} mm Hg. The arc current loop produces a magnetic field which bucks the dc field. H is into the picture. (b) Peak current is 1200 amperes, pressure is 1.2×10^{-3} mm Hg. The arc current loop produces a magnetic field which bucks the dc field. H is out of the picture. (c) Peak current is 1000 amperes, pressure is 2.2×10^{-3} mm Hg. The arc current loop produces a magnetic field which aids the dc field. H is out of the picture.

Figs. 15 and 16 and the spiral trajectories shown in Figs. 17 and 18.

We are, therefore, obliged to bring forward, *a posteriori*, a mechanism which will explain, at least qualitatively, these peculiar effects: The tight confinement of the plasmoid in the x and y directions (see Fig. 8) can be understood in terms of the diamagnetic depression produced in the magnetic field (see Fig. 6, third trace). The electric field observed in the laboratory system (see Figs. 6 and 7) can be understood in terms of $\mathbf{E}=-\mathbf{v}\times\mathbf{H}/c$. The apparent hollow structure (see Figs. 5, 7, and 8) can perhaps be understood in terms of an angular rotation or spin of the plasmoid, where centipetal effects produce the concentration of ion density at the periphery. However, this effect and its explanation calls for concerted experimental and theoretical effort before any firm conclusions can be drawn. The orbits in the laboratory system of the individual positive ions and electrons can be understood in terms of the polarization electric field ($=\mathbf{E}$) produced by the plasma moving across $\mathbf{H}$ with a speed $\mathbf{v}$ [see Fig. 20(a)]. With a fairly good vacuum (10^{-5} to 10^{-6} mm Hg) in the chamber, it is to be expected that practically no collisions between ions or electrons and residual gas atoms occur, and that practically no photoionization of the residual gas by the recombination photons will occur. However, at a pressure of about 10^{-3} mm of Hg (presumably mostly air and deuterium, with some pump-oil vapor) we can expect some photoionization throughout the chamber. We would not, however, expect an appreciable effect from collisions between the ions and electrons projected by the source and the residual gas atoms, because the mean free path for these collisions is still many times the dimensions of the vacuum chamber, and many times the Larmor radii of both positive ions and electrons.

The electrons produced by the photoionization can conceivably give rise to currents drived by the vector $\mathbf{E}=-\mathbf{v}\times\mathbf{H}/c$. These currents will of course act like an electromagnetic brake, reducing $\mathbf{v}$ and $\mathbf{E}$ progressively. This progressive reduction in $\mathbf{E}$ can conceivably [see Fig. 20(b)] give rise to a deflection of $\mathbf{v}$ into a spiral trajectory. The increased integrated illumination from the center of the photographs in Figs. 17 and 18 is evidence of a diminution in $\mathbf{v}$ in conjunction with a spiraling of $\mathbf{v}$. The fact that $\mathbf{v}$ spirals instead of executing a circle can be understood by realizing that as $\mathbf{v}$ decreases there will be more photoionization in a given region. The increased photoionization will increase the braking action and will further reduce $\mathbf{v}$. Thus the process of reduction in $\mathbf{v}$ is expected to be regenerative, and a spiral can conceivably result.

The interaction of plasmoids in the manner shown in Figs. 15 and 16 can now perhaps also be understood in terms of the mechanism depicted in Fig. 20, where in this case the presence of one plasmoid can produce conduction electrons in the presence of the other (and vice versa). The deflecting mechanism is then operative in some cases over a relatively limited length of trajectory [e.g., Fig. 15(a)].

Plasmoids are an example of a large-amplitude, magnetohydrodynamic phenomenon in a compressible medium. They apparently form naturally, and though they have only a transient existence (due to recombination loss and increasing resistivity), they nevertheless must represent a higher entropy state than a completely homogenized ensemble of magnetic field and plasma. The spontaneous tendency of an ionized gas in a magnetic field to undergo magnetohydrodynamic oscillations[2,3] is, therefore, very likely an example of this

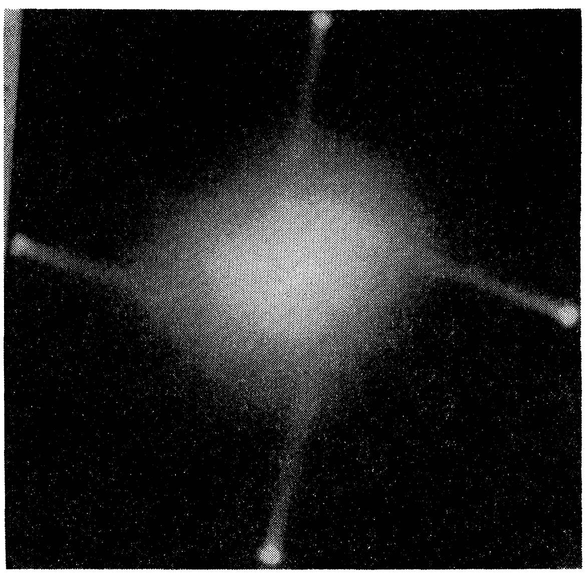


FIG. 19. Photograph similar to those of Fig. 18 except that by means of a filter, only the light of H_α (i.e., D_α) was used. The deuterium in the plasma comes from the electrodes of the arc, which are constructed of deuterium-loaded titanium. The sources were fired 20 times in order to get enough integrated light for this picture.

natural tendency to form plasmoids. However, the presence of conduction electrons that are stationary in the laboratory system can brake (lower) the speed of plasmoids, and can therefore conceivably damp the spontaneous magnetohydrodynamic oscillations in an ionized gas in a magnetic field.

It is possible to apply the knowledge gained concerning the nature of plasmoids to a hypothesized process of galaxy formation already advanced,[4] where gravitational contraction of ionized plasma across a magnetic field can lead to Taylor instability with resulting jets which should be accelerated toward the center of the gravitational attraction. These Taylor-instability jets may be expected to become plasmoids just as the four

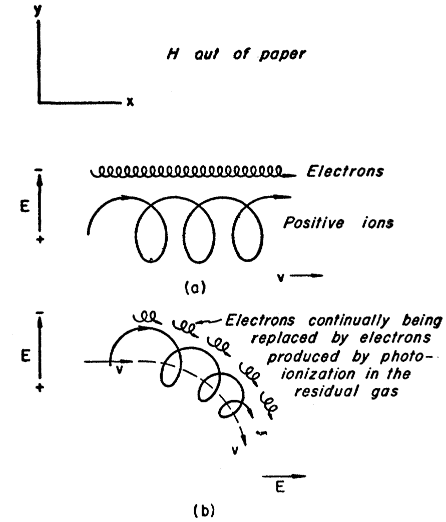


FIG. 20. Orbits of individual ions and electrons in the laboratory system as they move across the field **H** with a velocity v. (a) The case where there is a good vacuum and **v** and **E** are constant. (b) The case where v and E are decreasing with time. Presumably this is the case that can be produced with a poor vacuum.

plasma guns in Fig. 16 generate four plasmoids that proceed roughly radially inward. The spiralling toward the center by the proposed Taylor-instability plasmoids in the galaxy is to be expected as they approach the higher atomic density in the center and as they react on one another. The initial peripheral component of velocity of the Taylor-instability jets in the galaxy can conceivably be acquired by a process that is just the reverse of that diagrammed in Fig. 20(b): With the Taylor-instability jets the velocity (and hence **E**) will be expected to be initially *increasing* with a consequent deflection in the proper peripheral direction. An initial deflection (of the proper sign) of a plasmoid in a magnetic field is, in fact, observed to occur at the plasma gun itself. However, a program of quantitative measurements on this effect is required in order to analyze the phenomenon more accurately.

ACKNOWLEDGMENTS

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[2] W. H. Bostick and M. A. Levine, Phys. Rev. **97**, 13–21 (1955).
[3] W. H. Bostick and M. A. Levine, Phys. Rev. **87**, 671 (1952).
[4] W. H. Bostick, Phys. Rev. **100**, 1007–1008 (1955).

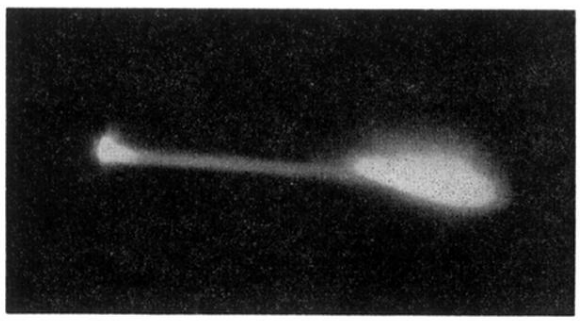


FIG. 10. Time-exposure photograph of trajectory of a plasmoid projected across a magnetic field of 1400 gauss. The electrodes of the source are oriented as shown in Fig. 2. The arc current of 3000 amperes is directed so that its magnetic field within its loop opposes the dc magnetic field. Note the two parallel lines of illumination with a dark septum in between.

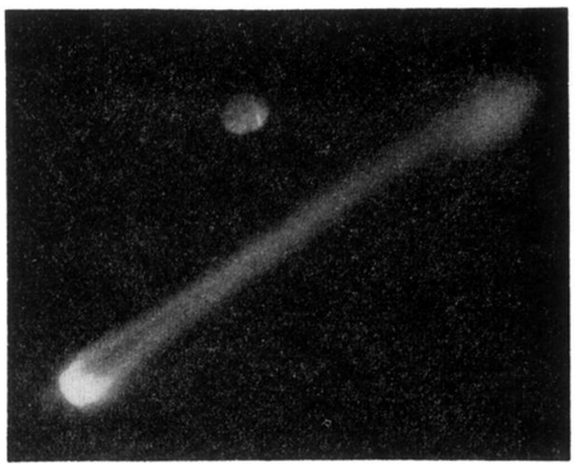


FIG. 11. Same as Fig. 10 except that the source arc current is reversed and the magnetic field is 4000 gauss. Note the wider spread between the lines.

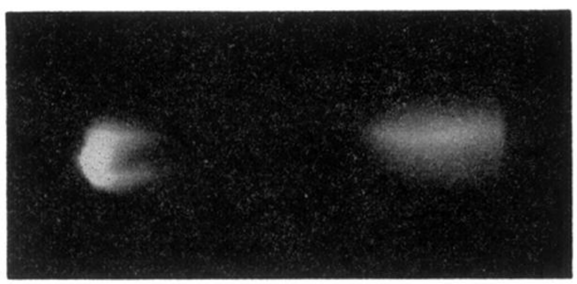
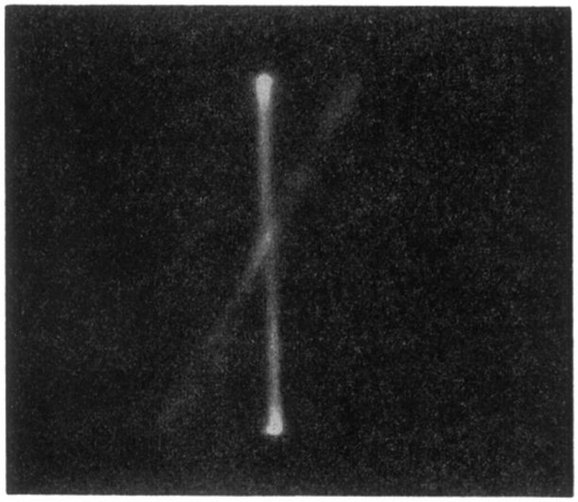
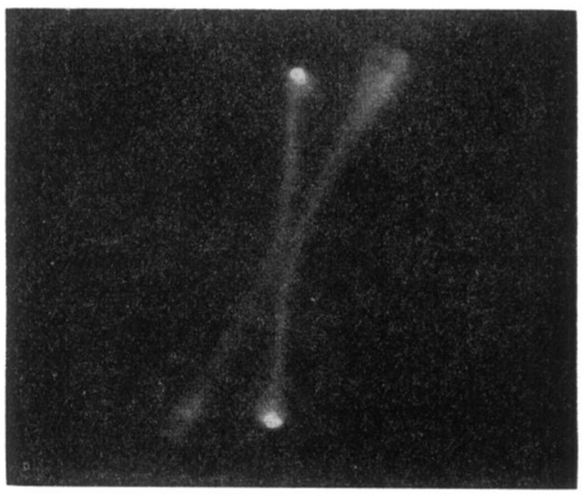


Fig. 12. Same as Fig. 10, except that the source electrodes are oriented so that initially the arc current is parallel to the magnetic field (see Fig. 14).



(a)



(b)

FIG. 15. Trajectories of plasmoids fired simultaneously at one another across a magnetic field at a pressure of 10^{-5} mm Hg with a separation distance of 10 cm. (a) $H=2000$ gauss, peak current is 1500 amperes, the impact parameter is small. (b) $H=4000$ gauss, peak current is 2700 amperes, the impact parameter is larger than in (a).

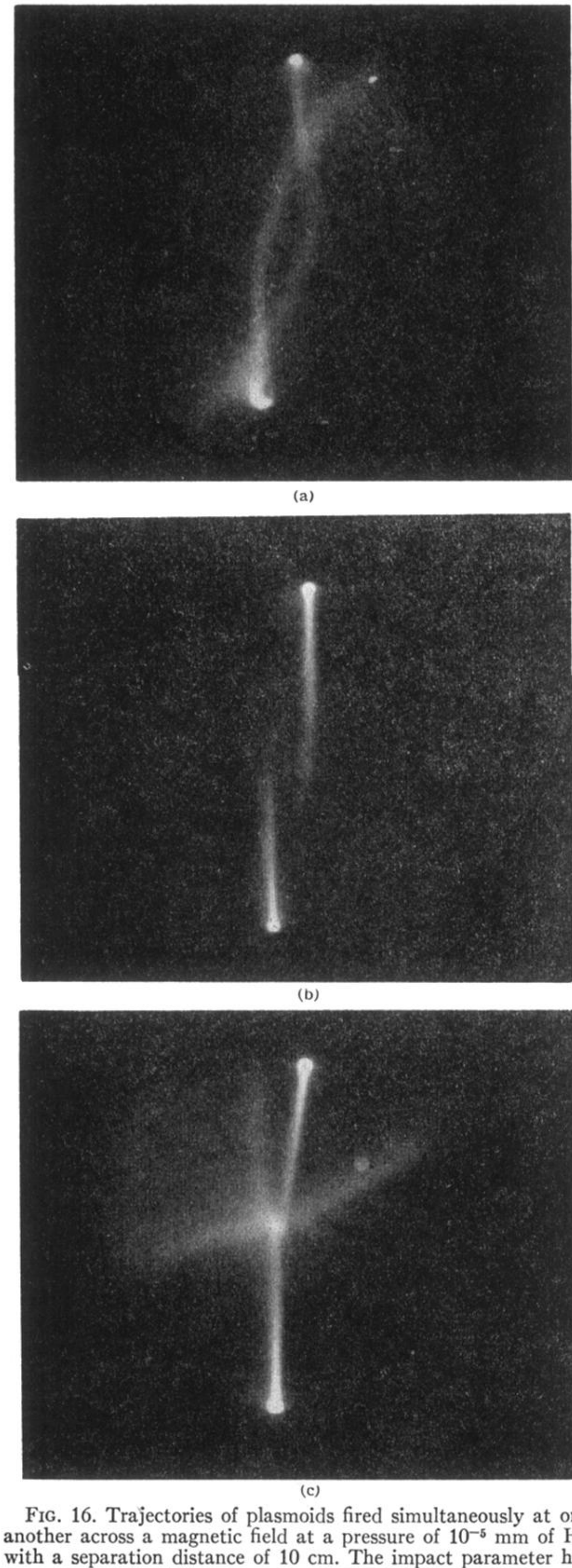


FIG. 16. Trajectories of plasmoids fired simultaneously at one another across a magnetic field at a pressure of 10^{-5} mm of Hg with a separation distance of 10 cm. The impact parameter has been changed in sign compared with Fig. 15. (a) $H=4000$ gauss, peak current is 2700 amperes. (b) $H=2000$ gauss, peak current is 1500 amperes. (c) $H=4000$ gauss, peak current is 2700 amperes. Here the plasmoids collide and break into fragments.

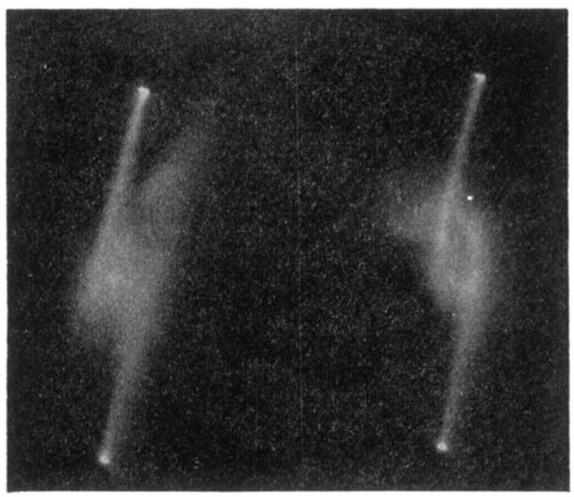


FIG. 17. Two plasmoids fired at one another across a magnetic field (into picture) of 4000 gauss at a pressure of 2.5×10^{-3} mm of Hg. The peak current in the source is 2700 amperes.

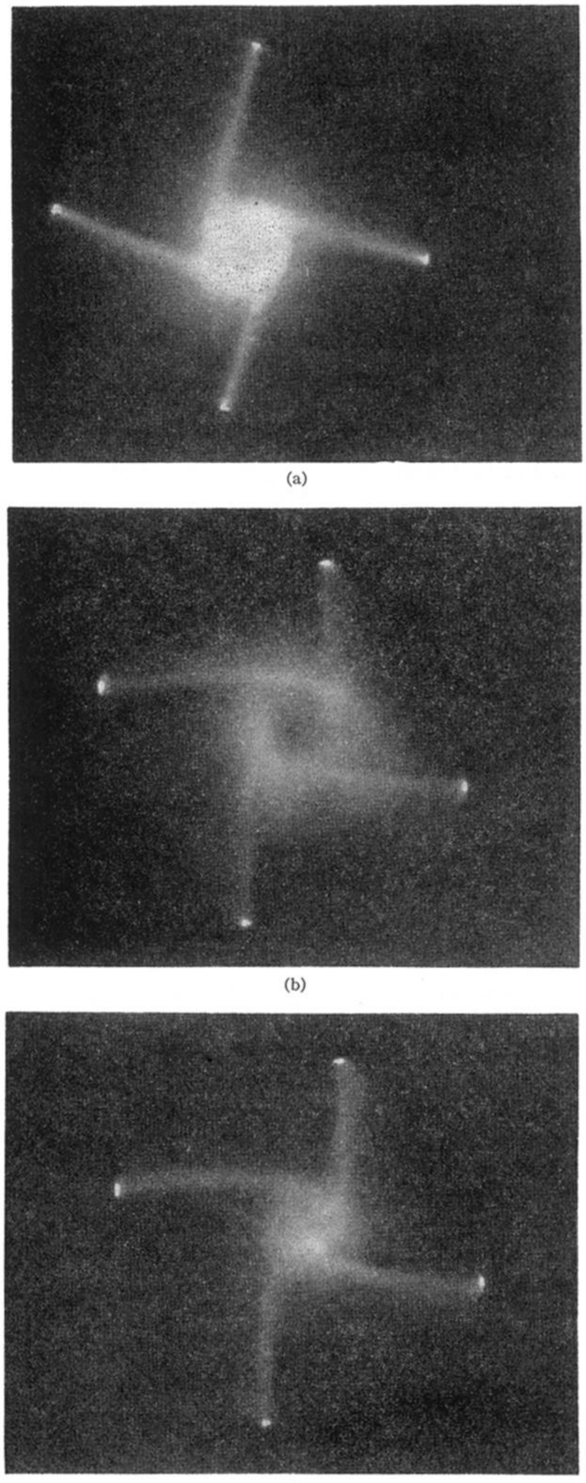


FIG. 18. Trajectories of four plasmoids fired simultaneously across a magnetic field of 4000 gauss. (a) Peak current is 2500 amperes, pressure is 2.5×10^{-3} mm Hg. The arc current loop produces a magnetic field which bucks the dc field. H is into the picture. (b) Peak current is 1200 amperes, pressure is 1.2×10^{-3} mm Hg. The arc current loop produces a magnetic field which bucks the dc field. H is out of the picture. (c) Peak current is 1000 amperes, pressure is 2.2×10^{-3} mm Hg. The arc current loop produces a magnetic field which aids the dc field. H is out of the picture.

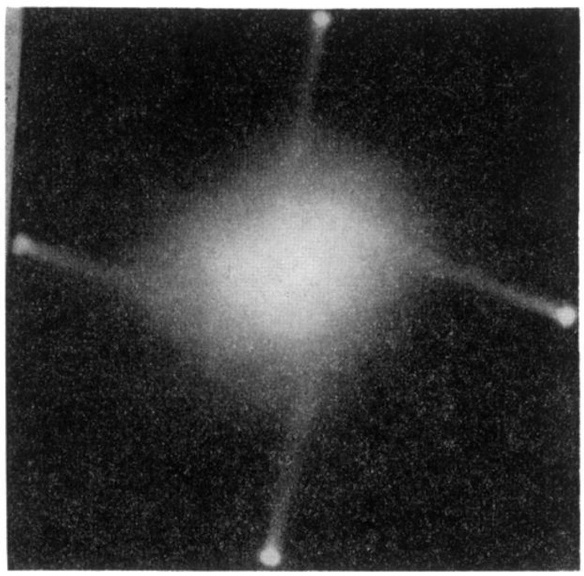


FIG. 19. Photograph similar to those of Fig. 18 except that by means of a filter, only the light of H_α (i.e., D_α) was used. The deuterium in the plasma comes from the electrodes of the arc, which are constructed of deuterium-loaded titanium. The sources were fired 20 times in order to get enough integrated light for this picture.

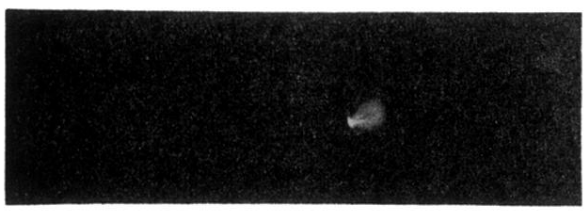


FIG. 3. Kerr-cell photograph, 0.5-μsec exposure, 0.5-μsec delay, of the profile of the luminous plasma ejected by firing a button source (see Fig. 1) at a peak current of 2000 amperes for approximately 0.2 μsec, with no external magnetic field applied. The actual length of the luminosity in the picture is 4 cm. A poor vacuum ($\sim 10^{-3}$ mm of Hg) slowed the plasmoid down somewhat and thereby rendered more light for the photograph.

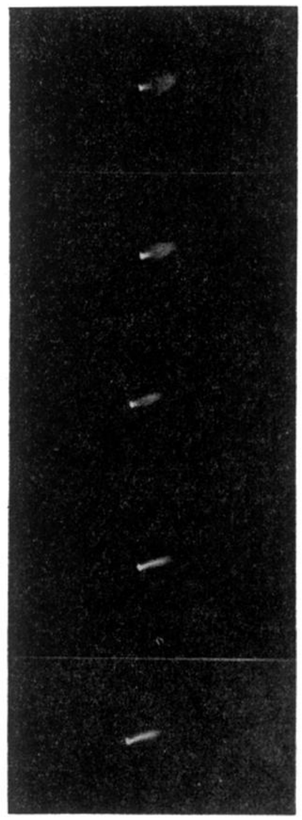


FIG. 5. Kerr-cell photographs taken under the same circumstances as Fig. 3, except that magnetic fields (geometry as shown in Fig. 2, with field out of paper) of values 600, 1200, 1800, 2400, and 3000 gauss have been applied. Note the squeezing effect in the vertical direction and the consequent tendency to form an elongated hairpin-like loop.

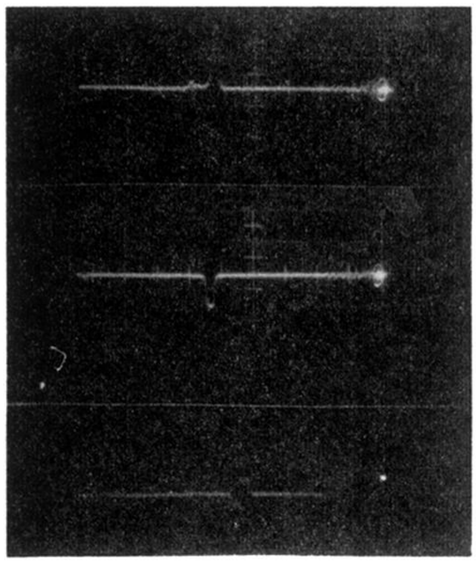


FIG. 6. The first two traces show signals measuring $\mathbf{E} = -\mathbf{v} \times \mathbf{H}/c$ picked up by two small probes 0.5 cm apart. The sweep speed is 0.5 μsec per cm, with time going from right to left. The peak current in the source is about 1800 amperes with a pulse duration of about 0.2 μsec. The first two traces are taken with sensitivities of 15 volts per cm and with magnetic fields (2000 gauss) in opposite directions. The third trace, taken with a sensitivity of 0.5 volts per cm shows the diamagnetic effect of a plasmoid as it passes a magnetic coupling loop 0.64 cm in diameter terminated in 50 ohms. The pulsed arc current in the source is in such a direction as to create a magnetic field which opposes the dc magnetic field for all the traces.

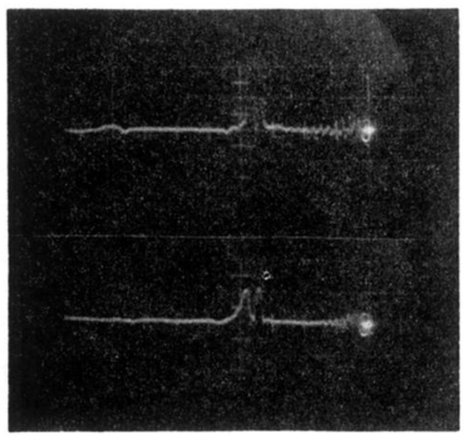


FIG. 7. Signals obtained with the same source and double probe configuration and same magnetic field (2000 gauss) as those in Fig. 6, except that the direction of arc current in the source has been reversed and increased to 3000 amperes. The sweep speed is 0.5 μsec/cm with time going from right to left. The sensitivity is 50 volts per cm for the first trace and 15 volts/cm for the second trace. The two peaks are believed to indicate a shell-like ion density distribution. It is typical that the plasmoids taken under the conditions of Fig. 7 travel faster than those of Fig. 6.

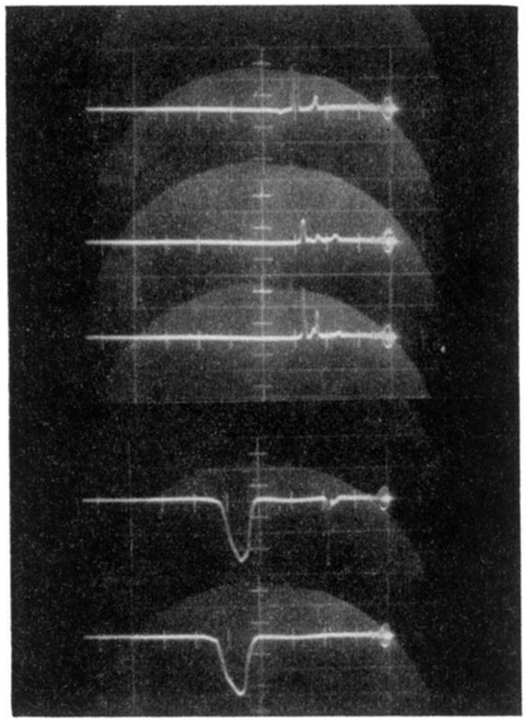


FIG. 9. Probe traces taken at a distance 10 cm from the source with a single probe which can be moved in the y direction to intercept either or perhaps both of the two plasmoids that are emitted and follow slightly different trajectories. The sensitivity is 5 volts/cm and the sweep speed is 1.0 μsec/cm. Traces 1, 2, 3 represent the probe on the x axis. Traces 4 and 5 represent the probe displaced 3 cm in the y direction. The dc magnetic field is 2000 gauss. The pulse current of 3000 amperes in the source produces a magnetic field that opposes the dc magnetic field.