Experimental Investigations of the Motion of Plasma Projected from a Button Source across Magnetic Fields*

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The velocity with which the plasma from a button source propagates across magnetic fields has been measured as a function of the experimental parameters. These experiments revealed that the velocity of the plasma front is a slowly varying function of the magnetic field strength from one to six kilogauss and increases monotonically with the voltage applied to the source condensers. Measurements of the arrival time of the plasma front *versus* distance from the source show that it moves across the magnetic field with constant velocity. When the source orientation is such that the force exerted by the magnetic field on the discharge current is in the direction of propagation the velocity is increased, and vice versa.

I. INTRODUCTION

THE experiments reported here are a continuation of the work of one of the authors (W.H.B.) and his co-workers in which a "blob" of plasma is fired from a button source in a direction perpendicular to a magnetic field.[1–6] The great variety of curious and unexpected phenomena observed seem to indicate that the plasma does not move as an amorphous "blob" but must possess some sort of structure which is stable for the length of time involved in the experiments (a few microseconds). We shall refer to this structure as a *plasmoid*. The purpose of the series of experiments reported here is to gain some insight into the structure of these plasmoids, the way in which they are formed, and the mechanism by which they move across magnetic fields.

Undoubtedly the simplest method of observing plasmoids is the use of photographic time exposures of their recombination light as they cross the magnetic field. This method has been widely used and has proven invaluable—particularly for the study of the interaction of two or more plasmoids. It of course yields no information on the electric or magnetic properties of the plasmoid, its velocity, or extension in the direction of motion. These properties are best investigated by the use of electrical probes (or, in the case of magnetic effects, loop probes).

Most of the work reported here has been concerned with the simplest quantitative data that can be obtained from probe measurements with good reproducibility; namely, the velocity of the front edge of the plasmoid as a function of significant experimental parameters such as magnetic field strength, the voltage applied to the condensers which are discharged through the source, and the orientation of the source with respect to the magnetic field. In order to obtain reproducible velocity measurements, we found it necessary to use a probe several centimeters in length, so that there would be no possibility of the plasmoid missing the probe or merely grazing the tip. Unfortunately, such long probes can yield little information about the interior structure of the plasmoid. They probably distort or destroy the structure of the plasmoid in the immediate vicinity of the probe.

In studying a phenomena whose nature is still mostly a matter of speculation, it seems worthwhile to perform experiments which have no other motivation than the possibility that something interesting may happen. Several experiments of this type are reported in Sec. VIII.

The experimental apparatus has been reported elsewhere.[1–6] In all the experiments described below, the capacity of the source condensers was 0.12 microfarad unless indicated otherwise. A brief description of each experiment and its principal results follows.

II. PROFILE OF THE PLASMOID FRONT

In this experiment the probe was moved along the lines of the magnetic field and hence perpendicularly to the trajectory of the plasmoid. The orientation of the source was such that the current in the arc was parallel to the magnetic field. The time of the first probe signal corresponding to the arrival of the leading edge of the plasmoid was measured and is shown plotted against the distance of the probe from its central position in Fig. 1. Also shown is the expected time of arrival if the plasma is emitted from the source with a constant radial velocity independent of angle.

III. ARRIVAL TIME *vs* DISTANCE OF PROBE FROM SOURCE

The time of arrival of the plasmoid front was measured as a function of the separation distance between

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† On leave of absence from the Naval Research Laboratory, Washington, D. C.
[1] W. H. Bostick, University of California Radiation Laboratory Reports UCRL-4478, 1955 and UCRL-4487, 1955 (unpublished).
[2] Bostick, Zizzo, and Cook, University of California Radiation Laboratory Report UCRL-4423, 1954 (unpublished).
[3] Bostick, Lasher, Finkelstein, and McIntosh, Atomic Energy Commission Report TID-7503, 1956 (unpublished), pp. 355–372.
[4] Bostick, Lasher, and McIntosh, Atomic Energy Commission Report TID-7503, 1956 (unpublished), pp. 373–9.
[5] W. H. Bostick, University of California Radiation Laboratory Report UCRL-4695, 1956 [Phys. Rev. **104**, 292 (1956)].
[6] V. G. McIntosh and W. H. Bostick, University of California Radiation Laboratory Report UCRL-4688, 1956 [Rev. Sci. Instr. (to be published)].

the source and probe for constant field strength and source voltage. In this experiment three orientations of the source were used. They were: (a) The current in the arc was perpendicular to the magnetic field and in such a sense that the force due to the interaction of the source current and external field would tend to increase the velocity of the plasmoid. (b) Same as above, except the source current had the opposite sense so that the force would tend to decrease the velocity. (c) Current in the source was parallel to the field; in this case the external field would exert no force on the current. The experiment was repeated for each of the three source orientations for two values of the source voltage. The results are shown in Figs. 2 and 3.

It will be noticed that the arrival time varies linearly with the separation distance, indicating that once the plasmoid is formed its front moves with constant velocity across the field. This was an unexpected result —particularly in view of the fact that the magnetic field must have varied considerably along the trajectory

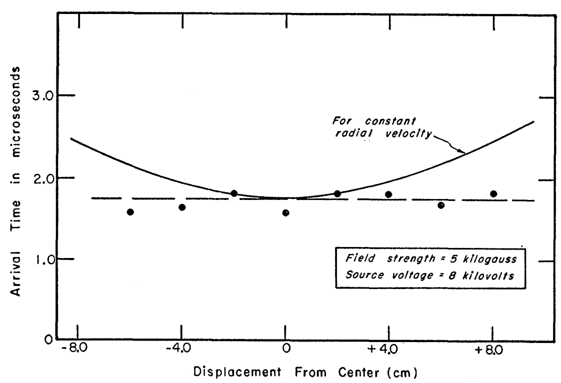

FIG. 1. Profile of the plasma front.

of the plasmoid. Indeed, a separation distance of 15 cm places the probe outside of the field coils where the field must have become quite small and perhaps have reversed its sign.

The slopes of the curves yield velocities for the source orientations (a), (b), and (c) of 9.1, 6.5 and 7.9 cm/μsec with a 10-kilovolt source voltage and 7.3, 4.4 and 5.2 cm/μsec with a 5-kilovolt source voltage. This dependence of the velocity on the source orientation is qualitatively what should be expected. That is, when the orientation of the source is such that the external magnetic field should increase the velocity, the velocity is indeed increased and *vice versa.*

IV. VELOCITY *vs* SOURCE VOLTAGE

The voltage applied to the source condensers was varied and the magnetic field was held constant. The velocity was obtained by dividing the separation distance between the source and probe by the arrival time, making no allowance for the finite time required

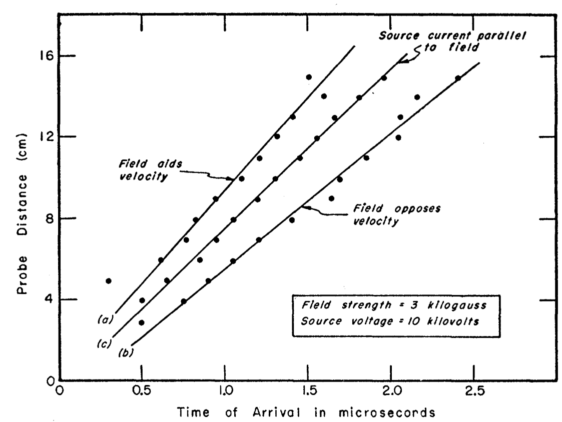

FIG. 2. Arrival time *vs* probe distance (source voltage 10 kv).

for the formation of the plasmoid. The experiment was performed with the three source orientations of Sec. III for two values of the magnetic field and source voltage. Velocity measurements were also made for the case of zero magnetic field. The experimental results are shown in Figs. 4, 5, and 6.

It is seen that the velocity increases smoothly with the source voltage as well as displaying the expected dependency on the source orientation. The unusual behavior of the velocity-*vs*-source voltage curve for the case of zero magnetic field should be noted in Fig. 6. An abrupt change in the velocity is seen in the neighborhood of 7.5 kilovolts. Apparently something drastic happens in the way the plasmoid is formed at this voltage. This is even more strikingly demonstrated by the shapes of the probe signals. Above 7.5 kv the signals vary smoothly with time, being first negative and then positive later. As the voltage is decreased below 7.5 kv, the signals rapidly degenerate into uninterpretable hash. A possible explanation is that for high currents through the arc of the source the plasma is contained by the pinch magnetic field, and some order is introduced into its subsequent expansion.

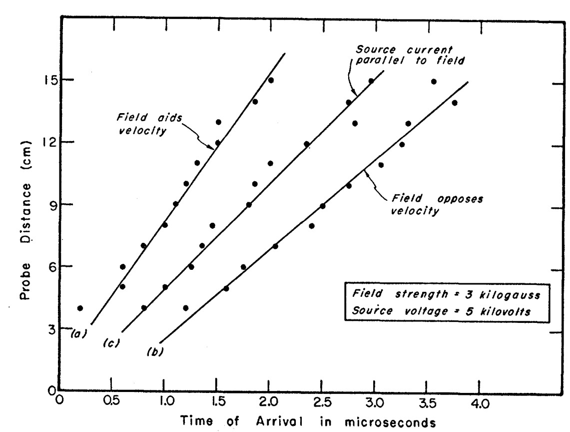

FIG. 3. Arrival time *vs* probe distance (source voltage 5 kv).

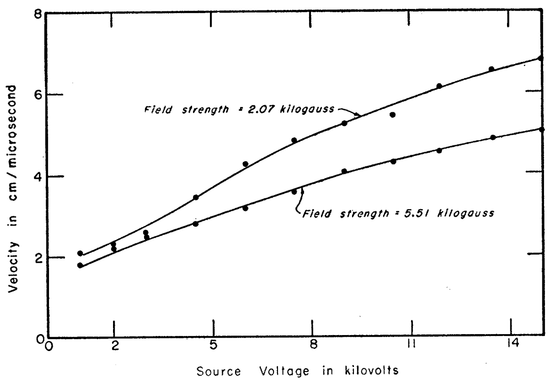

FIG. 4. Velocity *vs* source voltage with source current parallel to field.

For lower currents the pinch magnetic field is unable to contain the plasma.

V. VELOCITY *vs* ENERGY STORED IN THE SOURCE OF CONDENSERS

The question arose as to whether the velocity of the plasmoid was simply a function of the energy discharged (and hence the peak current) through the source or not. Consequently 1, 2, 3, and 4 condensers in parallel were discharged through the source, the voltage being adjusted in each case so that the energy stored would be the same. These results are shown in Table I for four different values of energy.

The velocity is seen to be only a function of the energy discharged (and hence the peak current) through the source within the experimental errors.

VI. VELOCITY *vs* MAGNETIC FIELD

The voltage applied to the source condensers was held fixed, the magnetic field was varied, and the velocity was determined as in Sec. IV. The experiment was repeated for two values of the source voltage for each of the three source orientations. The results are shown in Figs. 7 and 8.

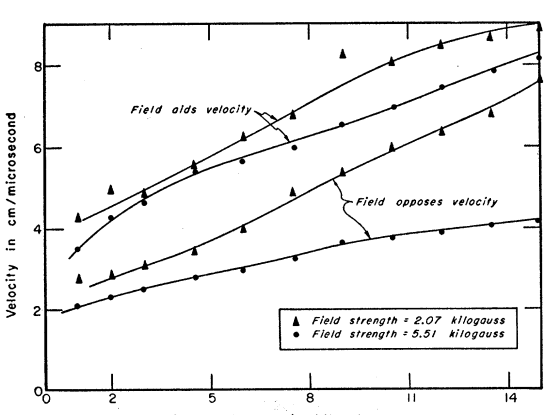

FIG. 5. Velocity *vs* source voltage.

A surprisingly small influence of the magnetic field on the plasmoid velocity is indicated over the range from 1 to 6 kilogauss. It is interesting to note that for the 5-kilovolt source voltage and orientation (a) of Sec. III, the velocity actually increases with increasing field strength.

VII. POLARIZATION EXPERIMENT

A conducting body moving through a magnetic field should become polarized. The polarization field is given by

$$\mathbf{E} = -(1/c)\mathbf{V}\times\mathbf{H}.$$

For a magnetic field of 3000 gauss and a velocity of 10^6 cm/sec, both of which are easily attainable, this gives an electric field of 30 volts/cm, which should be easily measurable.

To detect the polarization, we constructed a probe in the form of a dipole with the electrical connections at the center. This was placed in the beam from the source in such a way that the positively charged part of the plasmoid would hit the upper half of the dipole and the negatively charged part would hit the lower half. If the direction of the magnetic field was reversed or if the probe was rotated 180°, the signal was expected to change sign. If the probe was placed parallel to the field, no signal was expected. The probe behaved as was expected. Three probe signals for the different probe orientations are shown in Fig. 9. An attempt to obtain quantitative data from the signal (polarization field *vs* magnetic field, etc.) was not successful. We attributed this to the difficulty of striking the probe with the plasmoid in the same way under all conditions.

TABLE I. Velocity (in cm/μsec) *vs* energy stored in source condensers.

Energy \ No. of μf	0.3	0.6	0.9	1.2
E_1	5.3	5.1	5.1	5.1
E_2	5.8	5.6	5.6	5.6
E_3	7.0	6.7	7.0	6.2
E_4	7.9	7.7	7.5	7.0

VIII. MISCELLANEOUS EXPERIMENTS

We shall briefly describe some experiments which produced no quantitative data but had rather interesting results. We tried to shoot the plasmoid through a small hole in a baffle. A hole of 0.65-cm diameter was cut in a copper plate. This was placed in front of the source. With or without a magnetic field, plasma passed through the hole. This was observed both photographically and with a probe. With a magnetic field the stream of plasma stretched out in a direction parallel to the field and perpendicular to its velocity, as was the case in the preceding experiments.

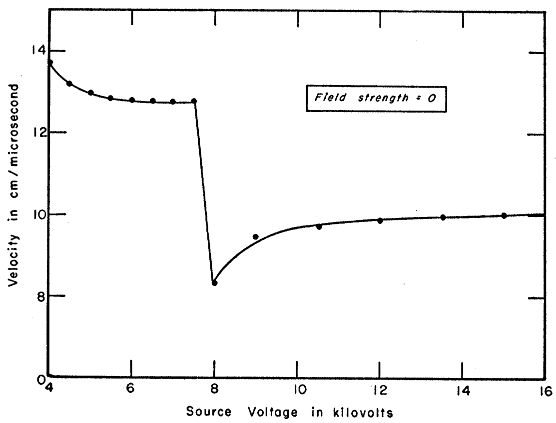

FIG. 6. Velocity *vs* source voltage at zero magnetic field.

A wire screen with a 2-mm mesh was placed in front of the source. The plasmoid passed through the screen. This was observed photographically.

It was thought that since plasmoids scatter one another, perhaps they could be bounced from a copper plate. A copper plate was inclined at an angle to the plasmoids' trajectory and placed in front of the source. Its face was parallel to the magnetic field. Time-integrated photographs revealed that the plasmoids did not bounce from the plate.

Both theory and experiments indicate that a plasmoid should be electrically polarized in a direction perpendicular to both its velocity and the magnetic field. It seemed likely that if this field were to be shorted out by a stationary conductor, the plasmoid would be brought to a stop. A copper plate was inserted into the system. It was orientated in such a way that it was perpendicular to the magnetic field. It was placed so that its edge would bisect the plasmoid. The results were not those that were anticipated since time-integrated photographs revealed that the plasmoid completely traversed the region of the copper plate.

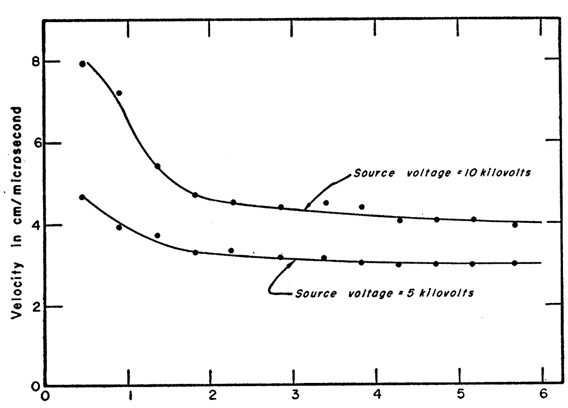

FIG. 7. Velocity *vs* magnetic field with source current parallel to field.

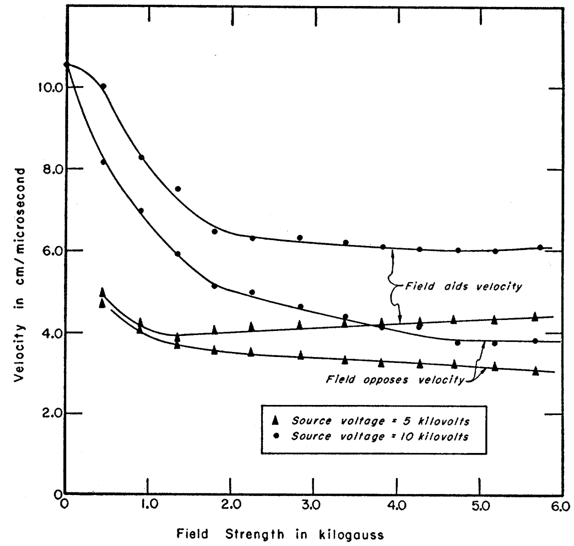

FIG. 8. Velocity *vs* magnetic field.

IX. CONCLUSIONS

In most of the experimental work that has been done thus far on plasmoids, unexpected results have been commonplace. It is gratifying to find some features of the behavior of plasmoids which are reasonable. This is the case in the qualitative dependence of the velocity of the plasmoid on the orientation of the source with respect to the external magnetic field and on the voltage applied to the source condensers. The flatness of the profile of the plasma front also is understandable in view of our measurements which show that the velocity is much greater for zero magnetic field than for finite field, and hence the plasmoid can be expected to expand more rapidly along the field lines than when it moves perpendicularly to them.

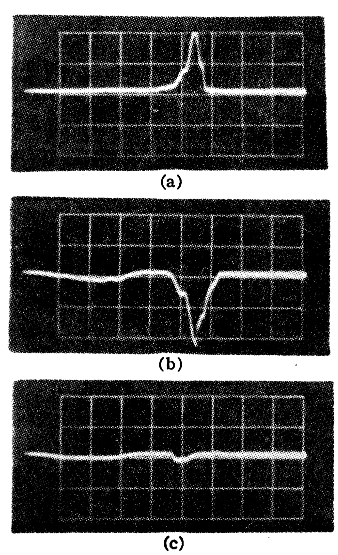

FIG. 9. Probe signals obtained with a polarization detector probe. (a) Probe orientated perpendicular to the field. (b) Probe rotated through 180°. (c) Probe orientated parallel to the field. In all cases the source voltage was 7 kv and the field was 3000 gauss.

Our measurements have been plagued by lack of reproducibility of the probe signals. This (together with a lack of understanding of the behavior of probes in a magnetic field) has restricted us in having to rely on the first arriving probe signal for quantitative data. Even this is not as reproducible as would be desired. This can be seen from the relatively large spread of the points about the experimental curves. Apparently, the way in which the source fires is sensitive to a number of factors which at present are uncontrollable.

At present we have only crude estimates of the number of ions emitted from the source and the composition of the resulting plasma (i.e., percentages of deuterium and titanium ions). We do not even know to what extent the many phenomena observed are peculiar to the titanium-deuterium source. A few experiments have been done with sources constructed from other electrode materials, but much further work needs to be done.

One experimental parameter which has not been varied in our experiments is the pressure of the residual gas. In the range of pressures (about 10^{-6} mm Hg) at which the experiments reported here were done, the residual gas is expected to have a negligible influence. At higher pressures (about 10^{-3} mm Hg) quite different phenomena have been observed. It would be of interest to extend the velocity measurements into the range of higher pressures.

ACKNOWLEDGMENTS

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Paramagnetic Resonance of Free Radicals at Millimeter Wave Frequencies*

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Paramagnetic resonance experiments have been made at 36 kMc/sec and at 75 kMc/sec on single crystals and on solid and liquid solutions of the free radicals: diphenyl picryl hydrazyl (DPPH), *p*-anisyl nitrogen oxide, and 2-(phenyl nitrogen oxide)-2-methyl pentane-4-one-oxime-*N*-phenyl ether. The measurements indicate fields axially symmetric about the paramagnetic element in the first two, with $g_{\parallel}=3.0035$, $g_{\perp}=2.0043$ for the first and $g_{\parallel}=2.0095$, $g_{\perp}=2.0035$ for the second. The third radical has a lower symmetry with $g_x=2.0042$, $g_y=2.0064$, and $g_z=2.0083$ along the principal axes of susceptibility. The hyperfine structure of DPPH in dilute solution (earlier observed by others) consists of five components, arising from interactions with the two N^{14} nuclei of the N^{14} group. The other two radicals of the present study were found to have in dilute liquid solution a triplet hyperfine structure arising from interaction with a single N^{14} nucleus. This structure is interpreted as indicating that the odd electron is localized mainly on an —N=O group in each radical. The anisotropies in the g factors are believed to arise mainly from a residual spin-orbit coupling. A sensitive millimeter-wave magnetic-resonance spectrometer employing superheterodyne detection with a crystal multiplier as the beat frequency oscillator is described.

INTRODUCTION

PARAMAGNETIC resonance measurements at millimeter-wave frequencies have certain advantages over those at lower frequencies. Because of the commensurately higher magnetic fields at the higher frequencies, the field-dependent components of the resonance are more widely separated. When there are in the sample two radicals with g factors differing only slightly, the resonances might overlap at the lower fields and be resolved at the higher ones. From the resonance condition, $h\nu=g\beta H$, it follows that when the observation frequency is held constant two components with g factors differing by a small Δg will occur at fields differing by:

$$\Delta H=(\Delta g/g)H=(\Delta g/g)(h\nu/g\beta), \tag{1}$$

if g is independent of H, as is found true for the radicals under investigation. Whenever ΔH is measurable at different frequencies, the higher the observation frequency the smaller is the Δg which can be detected and the more accurately a given Δg can be measured.

One of the three free radicals included in the present study, diphenyl picryl hydrazyl (DPPH), has already been investigated rather thoroughly in the lower centimeter-wave region. The resonance of this radical was first detected by Holden, Kittel, Merritt, and Yager.[1] Later it was found to have an N^{14} hyperfine structure in dilute solution by Hutchison, Pastor, and Kowalsky,[2] who also made measurements on single crystals and showed that the g factor is not exactly

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[1] Holden, Kittel, Merritt, and Yager, Phys. Rev. **75**, 1614 (1949); **77**, 147 (1950).
[2] Hutchison, Pastor, and Kowalsky, J. Chem. Phys. **20**, 534 (1952).

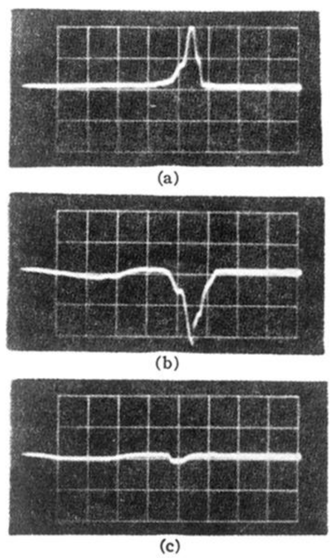

FIG. 9. Probe signals obtained with a polarization detector probe. (a) Probe orientated perpendicular to the field. (b) Probe rotated through 180°. (c) Probe orientated parallel to the field. In all cases the source voltage was 7 kv and the field was 3000 gauss.