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MEMORANDUM FOR DTIC

02 November 2017

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SUBJECT: Change the Distribution Statement from the DTIC-Applied C for the Progress Reports Associated with the Following AD Numbers: AD0203743, AD0213968, and AD1038383

The following progress reports, which were auto-assigned a Distribution Statement C by DTIC due to their absent distribution markings when submitted to DTIC in the late 1950s, have been reviewed by AFRL/RQ lead scientists who have specific knowledge in the subject matter contained in the progress reports, security personnel, and the 88th Air Base Wing Public Affairs Office agent, Jeannie Masters (jeannie.masters@us.af.mil)—each of the reports has been cleared for public release:

Research In The Measurements And Theory Of Plasmoids And Their Applications To Missiles And Satellite Technology

Progress Report 1, AD0203743 - 11 Sep 1958; 88ABW-2017-5445, Cleared on November 1, 2017

Progress Report 2, AD0213968 - 13 Mar 1959; 88ABW-2017-5446, Cleared on November 1, 2017

Progress Report 3, AD1038383 - 11 Jun 1959; 88ABW-2017-5447, Cleared on November 1, 2017

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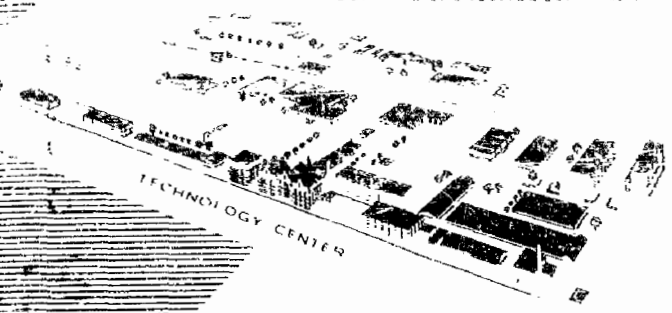
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88ABW-2017-5446

ARF

AMERICAN RESEARCH BUREAU OF HIGHER EDUCATION, ONE FORTY EIGHTS INSTITUTE OF TECHNOLOGY



ARF Project No. A 121

on

"RESEARCH IN
THE MEASUREMENTS AND THEORY OF
PLASMOIDS AND THEIR APPLICATIONS TO
MISSILES AND SATELLITE TECHNOLOGY"

Contract No. AF 33(516)-5791
(Task No. 70854)

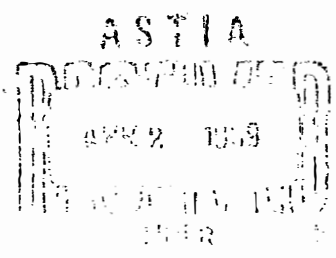
Progress Report No. 3

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PA Case Number: 88ABW-2017-5446; Clearance Date: 01 November 2017.

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RESEARCH FOR INDUSTRY



ARMOUR RESEARCH FOUNDATION

of

Illinois Institute of Technology
Technology Center
Chicago 16, Illinois

ARF Project No. A 121

on

"RESEARCH IN
THE MEASUREMENTS AND THEORY OF
PLASMOIDS AND THEIR APPLICATIONS TO
MISSILES AND SATELLITE TECHNOLOGY"

Contract No. AF 33(616)-5791
(Task No. 70854)

for

Aeronautical Research Laboratory, WCLJH,
Wright Air Development Center,
Wright-Patterson Air Force Base, Ohio.

Progress Report No. 2

Covering the period of December 1, 1958 to February 28, 1959

March 13, 1959

FC

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ABSTRACT

Y The plasmoids originally reported and studied by Bostick have been reproduced at this laboratory. Considerable knowledge has been gained of the experimental apparatus in the course of placing the unit in operation and making preliminary investigations. No quantitative measurements have yet been made, but several are underway at this writing. Time-exposure photographs have been made under various conditions and compared to those previously reported. The theoretical investigations of the stability of cylindrical plasma configurations have been continued; in this quarter a study was undertaken to determine the effect of rotation on stability taking into consideration the compressibility of the plasma. N

LIST OF APPENDICES

APPENDIX

- I. Hydromagnetic Study of Rotating Compressible Plasmas.
- II. Construction of the experimental Apparatus.
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"RESEARCH IN
THE MEASUREMENTS AND THEORY OF
PLASMOIDS AND THEIR APPLICATIONS TO
MISSILES AND SATELLITE TECHNOLOGY"

I. INTRODUCTION

The purpose of this project is to investigate theoretically the stability of cylindrical plasma configurations, determine experimentally the behavior of high energy plasmoids, and suggest what practical use might be made of plasmoids with respect to high-altitude vehicles. This report outlines the progress and planning of this project as of the end of the third quarter of the contract period on February 28, 1959.

II. THEORETICAL INVESTIGATIONS

Continuing our theoretical investigation of the stability of cylindrical plasma configurations, we have undertaken a hydromagnetic study of rotating compressible plasmas. Allowing for the compressibility of the plasma introduces many mathematical complications into the problem; but if these can be overcome, the results should be more directly applicable to plasmoids than those resulting from an analysis in which the plasma is considered incompressible.

The progress on the problem to date is outlined in Appendix I; at this point the next obstacle is the solution of three simultaneous differential equations in three unknown functions of a single variable. While these certainly can be solved in principle (e.g. by use of the Laplace transform) it is by no means certain that this will prove to be the best way of treating the problem. Another possibility which will be considered during the next quarter is the development of a variational principle by which to solve the problem approximately. The case in which the angular velocity Ω of the

plasma is not a constant but a function of the radial distance will also be considered.

Various aspects of the problems mentioned above have been considered by Dungey¹ and by Chandrasekhar² for an incompressible fluid, but it may be necessary to consider the incompressible case in detail before treating the compressible case; if so, it could easily take the entire quarter for this study.

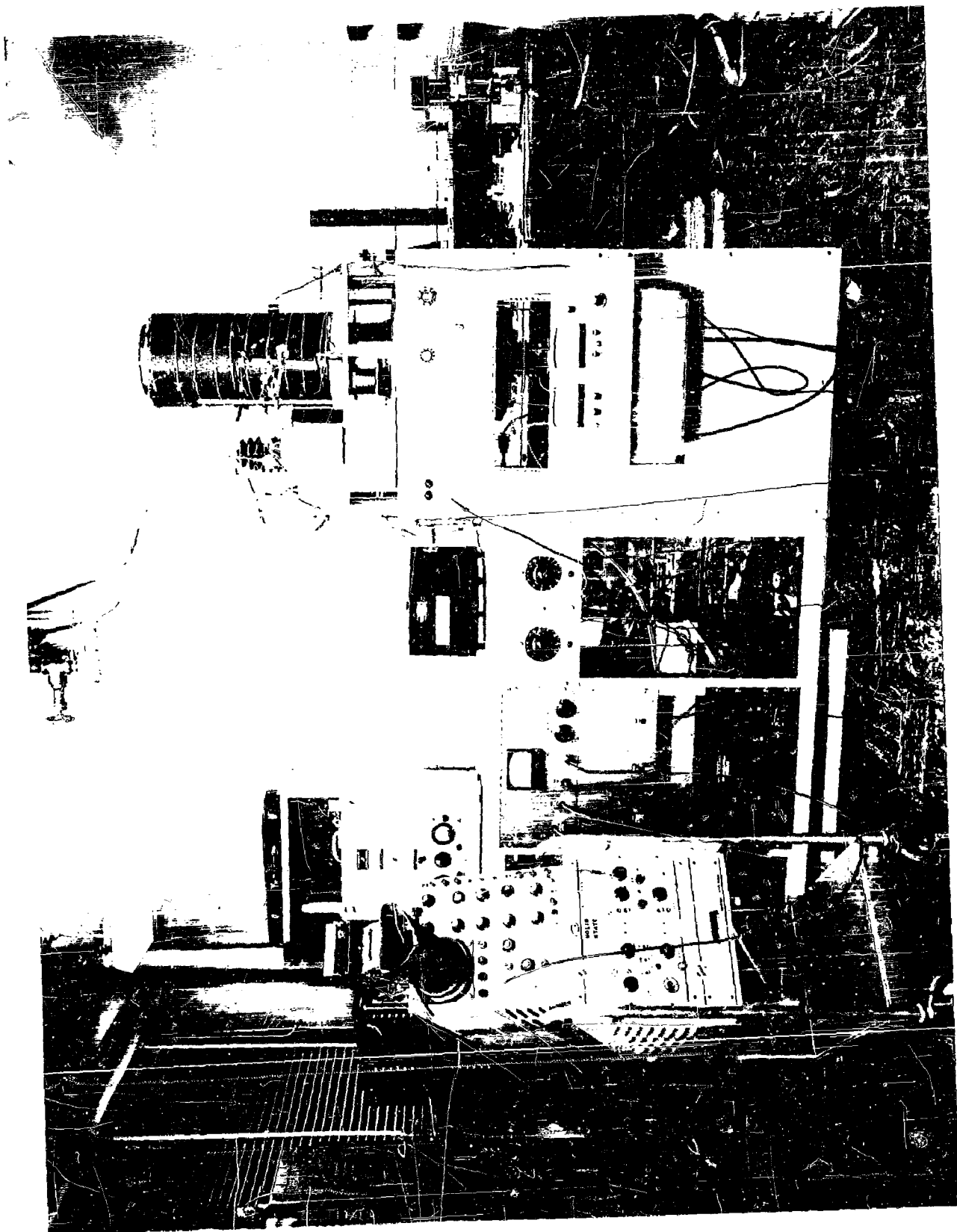
III. EXPERIMENTAL DESCRIPTION

The basic experimental unit has been completed and is being used for the work in progress. Fig. 1 shows the completed apparatus. Additions and modifications are being made for the individual experiments and improved operation. The development of the apparatus has progressed to a very satisfactory level and is described in Appendix II. Photographic techniques have been developed through the experience gained in the photographic work that has already been done.

There has been considerable progress on the electronic circuitry for an image converter light shutter. The design is basically that of a unit in operation at Los Alamos Scientific Laboratory. The design prints were obtained through Dr. J. Marshall of Los Alamos and our unit planned from there. Several of the components have been already completed, and the complete unit will be ready in about two months. The final unit on completion and final modification will be reported in the next report. The image converter will give us a very powerful research tool for stopping the motion of the plasmoids which will render a better understanding of their nature.

¹J. W. Dungey, Cosmic Electrodynamics (Cambridge, University Press 1958).

²S. Chandrasekhar, unpublished (private communication).



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The pictures shown and described in Appendix III are time-exposure photographs and necessarily lack detail. In addition, in each firing there are several plasmoids formed due to the ringing in the discharge circuit and the camera records the entire series of plasmoids. Probe measurements conducted showed a larger RF signal due to the resonating plasma source LC loop. The event sought with the probe measurement was completely swamped by the ringing signal. A damping resistor will be added to the discharge circuit to make the discharge unidirectional which should make probe measurements possible. The peak current will be reduced by about 1/2 in such an arrangement due to the damping of the resistor. The energy of the plasmoids will be reduced accordingly.

IV. FUTURE WORK

Photographic analysis will be continued and improved by the addition of a mirror to photograph the plasmoid at right angles to the field lines in addition to along the field lines. It is hoped that preliminary photographs can be made with the image converter at the very end of the next quarter.

The use of probes will be continued when a unidirectional pulse is in operation. Here it will be possible to measure the plasmoid velocity by time of flight. In addition the electric field strength and the diamagnetic perturbation of the D.C. magnetic field can be investigated with probes and coupling loops.

Optical measurements will be made with a photomultiplier telescope. This will provide information on the velocity of the plasmoids and their shape.

Microwave measurements will be inaugurated in this quarter as described in Appendix IV. It is anticipated that experience can be gained

and many of the problems reduced so that preliminary measurements can be made by the end of this quarter.

V. LOGBOOK REFERENCES

The data of this project are recorded in ARF Logbook Nos. C-8026, C-8036, C-8319, C-8326, C-8388, C-8456, C-8531, C-1025, C-8538, C-8820, and C-8821.

VI. CONTRIBUTING PERSONNEL

The theoretical investigations are being carried out by Val W. Pratt, D. J. DeGeeter, J. T. Jones, and R. L. Watkins are responsible for design and construction of the apparatus and the planning of experimental investigations.

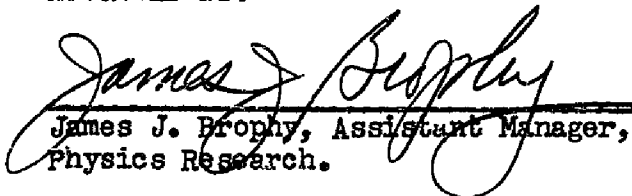
Respectfully submitted,

ARMOUR RESEARCH FOUNDATION
of Illinois Institute of Technology



Dale J. DeGeeter, Asst. Physicist,
Plasma and Electron Physics.

APPROVED BY:



James J. Brophy, Assistant Manager,
Physics Research.

APPENDIX I

HYDROMAGNETIC STUDY OF ROTATING COMPRESSIBLE PLASMAS

by

Val W. Pratt

ARMOUR RESEARCH FOUNDATION OF ILLINOIS INSTITUTE OF TECHNOLOGY

Appendix I

HYDROMAGNETIC STUDY OF ROTATING COMPRESSIBLE PLASMAS

The problem we shall consider is the following: A compressible, inviscid, perfectly conducting plasma cylinder of radius r_0 is rotating about its own axis (the z-axis of our cylindrical coordinate system) with angular velocity $\Omega(r)$, with a magnetic field of magnitude $B_0(r)$ everywhere parallel to the z-axis. We assume that in the steady state all quantities are independent of the azimuthal coordinate θ . The plasma cylinder is surrounded by a vacuum in which there is a magnetic field which may have θ - and z-components but no radial component. To give a boundary condition on the vacuum field, we assume that the vacuum space around the plasma is enclosed in a rigid conducting cylinder of radius R_0 . We can later remove this restriction by letting $R_0 \rightarrow \infty$.

The hydromagnetic equations we shall use are:

$$\rho \frac{\partial \vec{v}}{\partial t} + \rho (\vec{v} \cdot \nabla) \vec{v} = \frac{1}{4\pi} (\vec{B} \cdot \nabla) \vec{B} - \text{grad} \left(p + \frac{B^2}{8\pi} \right), \quad (1)$$

$$\frac{\partial \rho}{\partial t} = - \text{div} \rho \vec{v}, \quad (2)$$

$$\text{curl} \vec{B} = \frac{4\pi}{c} \vec{j}, \quad (3)$$

$$\text{div} \vec{B} = 0, \quad (4)$$

$$\text{curl} \vec{E} = - \frac{1}{c} \frac{\partial \vec{B}}{\partial t}, \quad (5)$$

$$\text{div} \vec{E} = 4\pi e, \quad (6)$$

$$\vec{E} + \frac{\vec{v} \times \vec{B}}{c} = 0, \quad (7)$$

$$\frac{1}{\rho} \frac{d\rho}{dt} = \frac{\gamma}{\rho} \frac{d\rho}{dt}, \quad (8)$$

where p , ρ , and γ are respectively the pressure, density, and ratio of specific heats of the plasma; \vec{E} and \vec{B} are respectively the electric and magnetic fields, \vec{j} the electric current, ϵ the net electric charge density, and \vec{v} the fluid velocity field.

The terms $(\vec{v} \cdot \nabla) \vec{v}$ and $(\vec{B} \cdot \nabla) \vec{B}$ in Eq.(1) must be interpreted properly in cylindrical coordinates:

$$\begin{aligned} [(\vec{v} \cdot \nabla) \vec{v}]_r &= \vec{v} \cdot (\text{grad } v_r) - \frac{v_\theta^2}{r}, \\ [(\vec{v} \cdot \nabla) \vec{v}]_\theta &= \vec{v} \cdot (\text{grad } v_\theta) + \frac{v_\theta v_r}{r}, \\ [(\vec{v} \cdot \nabla) \vec{v}]_z &= \vec{v} \cdot (\text{grad } v_z), \end{aligned} \tag{9}$$

where the extra terms in the r - and θ -components correspond respectively to centripetal and Coriolis accelerations. For a steady state of pure rotation, $\vec{v} = (0, r\Omega, 0)$, $(\vec{v} \cdot \nabla) \vec{v} = -r\Omega^2 \vec{1}_r$, where $\vec{1}_r$ denotes a unit vector in the radial direction. The $(\vec{B} \cdot \nabla) \vec{B}$ term gives no contribution from the magnetic field inside the plasma, where there is no r - nor θ -component, and the z -component depends only on r .

For the steady state within the plasma, Eq.(1) reduces to

$$-\rho_0 r\Omega^2 = -\frac{\partial}{\partial r} \left(p_0 + \frac{B_0^2}{8\pi} \right), \tag{10}$$

where the zero subscripts here denote the steady-state values. It is easily seen from equation (10) that we now cannot assume that p_0 , ρ_0 , B_0 , and Ω are all constants independent of r , for there would then be nothing to balance the centrifugal force in the equation. In the incompressible case it is possible to keep ρ_0 and B_0 constant and divide p_0 into a constant term plus a term whose

gradient balances the centrifugal force; the latter term can then be absorbed implicitly into the "generalized pressure" perturbation term and the problem carried through as though p_0 , ρ_0 , B_0 , and Ω were all constant.

In a compressible fluid, however, one cannot have p varying and ρ constant except by maintaining a temperature gradient in the fluid, which appears to be impossible in the plasmas under consideration. It would of course be possible to consider ρ varying with p in such a way that their ratio remained constant; but in view of the very short relaxation times of most plasmas, it appears more reasonable physically to assume that p_0 and ρ_0 both remain constant, so that B_0 must vary in such a way as to balance the centrifugal force.

Taylor¹ has investigated in some detail the stability of a non-rotating compressible plasma, and we shall use mostly his notation here, to facilitate comparison where possible between the two cases. We assume that the initial velocity field $\vec{v}_0 = (0, r\Omega, 0)$, the vacuum magnetic field $\vec{B}_0^v = (0, B_{\theta 0} \frac{r_0}{r}, B_{\theta 0} b_e)$, and the plasma magnetic field at the boundary $\vec{B}_0^p(r_0) = (0, 0, B_{\theta 0} b_i)$, so that b_i and b_e denote the ratios of the z-components of the interior and exterior fields respectively to the θ -component of the vacuum field at the boundary $r = r_0$. For the time being we shall assume Ω constant, as well as p_0 and ρ_0 , so that

$$\left| B_0^p(r_0) \right|^2 = B_{\theta 0}^2 b_i^2 - 4\pi \rho_0 \Omega^2 (r_0^2 - r^2). \quad (11)$$

¹ R. J. Taylor, Proc. Phys. Soc. (London) B70, 1049-1063 (1957).

Then, according to Eq.(3), there must be within the plasma an azimuthal current j_o , given by

$$j_o = - \frac{c}{4\pi} \frac{dB_o}{dr} . \quad (12)$$

We assume that the interior and exterior fields are balanced by an additional current $\vec{j}_o^* = (0, j_{o\theta}^*, j_{oz}^*)$ which flows on the surface of the plasma. The boundary conditions are that $(p + \frac{B^2}{8\pi})$ and the normal component of B shall each be continuous at the boundary. Thus the system will be in equilibrium if

$$\begin{aligned} j_{o\theta}^* &= \frac{cB_{\theta 0}}{4\pi} (b_i - b_e), \\ j_{oz}^* &= \frac{cB_{\theta 0}}{4\pi} , \\ p_c &= \frac{B_{\theta 0}^2}{4\pi} (1 + b_e^2 - b_i^2) . \end{aligned} \quad (13)$$

To examine the stability of the equilibrium, we linearize the equations of motion and examine the behavior of the system in the presence of small perturbations. With the equations linearized, any small perturbation may be represented as a superposition of fundamental modes. Therefore, we assume that any variable q takes the form

$$q = q_o + q_1 \exp [i (m\theta + kz) + \omega t] , \quad (14)$$

where q_o is the equilibrium value and $q_1 = q_1(r)$ is a first-order perturbation; we will neglect all second-order terms.

In the vacuum no current can flow, so Eq. (3) yields $\text{curl } \vec{B}_1^v = 0$; therefore the perturbation field can be derived from a magnetostatic potential ψ

so that

$$B_1^v = \text{grad } \psi . \quad (15)$$

Further, from Eq. (14) we see that ψ must satisfy Laplace's equation

$$\nabla^2 \psi = 0, \quad (16)$$

the solution of which is

$$\psi = C_1 K_m (kr) + C_2 I_m (kr), \quad (17)$$

where I_m and K_m are the modified Bessel functions of the first and second kinds² and C_1 and C_2 are constants to be determined from the boundary conditions. The components of \vec{B}_1^v then are

$$\begin{aligned} B_{1r}^v &= k C_1 K'_m (kr) + k C_2 I'_m (kr), \\ B_{1\theta}^v &= \frac{im}{r} C_1 K_m (kr) + \frac{im}{r} C_2 I_m (kr), \\ B_{1z}^v &= i k C_1 K_m (kr) + i k C_2 I_m (kr), \end{aligned} \quad (18)$$

where a prime denotes differentiation with respect to the argument. From the requirement that B_r must be continuous at the rigid conducting boundary we see that

$$B_{1r}^v (R_0) = 0, \text{ which yields}$$

$$\frac{C_1}{C_2} = - \frac{I'_m (k R_0)}{K'_m (k R_0)} \quad (19)$$

as one relation between the constants C_1, C_2 .

² The notation agrees with that of G. N. Watson, A Treatise on the Theory of Bessel Functions (Cambridge, University Press, second edition 1944).

Now combining Eq.(5) and (7) we have

$$-\frac{1}{c} \frac{\partial \vec{E}}{\partial t} = \text{curl } \vec{E} = -\frac{1}{c} \text{curl} (\vec{v} \times \vec{B}),$$

$$\frac{\partial \vec{B}}{\partial t} = \text{curl} (\vec{v} \times \vec{B}). \quad (20)$$

Linearizing Eq.(20) for the plasma in accordance with Eq.(14) yields the three component equations:

$$\omega B_{1r} = -im \Omega B_{1r} + ik B_0 v_{1r},$$

$$\omega B_{1\theta} = ik r \Omega B_{1z} + ik B_0 v_{1\theta} + \Omega B_{1r} + r \Omega D B_{1r}, \quad (21)$$

$$\omega B_{1z} = -B_0 D^* v_{1r} - v_{1r} D B_0 - im \Omega B_{1z} - \frac{im}{r} B_0 v_{1\theta},$$

where $D = \frac{d}{dr}$ and $D^* = (\frac{d}{dr} + \frac{1}{r})$. The solutions for the components of \vec{B}_1 in terms of the components of \vec{v}_1 are:

$$B_{1r} = \frac{ik B_0}{\sigma} v_{1r},$$

$$B_{1\theta} = \frac{ik B_0}{\sigma} v_{1\theta}, \quad (22)$$

$$B_{1z} = \frac{B_0}{\sigma} (ik v_{1z} - \text{div } \vec{v}_1) - \frac{v_{1r}}{\sigma} D B_0,$$

where $\sigma = \omega + im \Omega$.

From Eq.(2),

$$\omega \rho_1 = -\rho_0 \text{div } \vec{v}_1 - im \rho_1,$$

$$\rho_1 = -\frac{\rho_0}{\sigma} \text{div } \vec{v}_1. \quad (23)$$

Equation(8) now gives

$$\frac{\omega p_1}{\rho_0} = \frac{\gamma \omega p_1}{\rho_0} , \quad (24)$$

$$p_1 = c_s^2 \rho_1 = - \frac{\rho_0 c_s^2}{\sigma} \operatorname{div} \vec{v}_1$$

where $c_s^2 = \frac{\gamma p_0}{\rho_0}$, so that c_s is the speed of sound in the unperturbed plasma.

The current due to perturbations in the magnetic field is given by

Eq.(3):

$$j_{1r} = \frac{c}{4\pi} \left[\frac{im}{r} B_{1z} - ik B_{1\theta} \right] ,$$

$$j_{1\theta} = \frac{c}{4\pi} \left[ik B_{1r} - D B_{1z} \right] , \quad (25)$$

$$j_{1z} = \frac{c}{4\pi} \left[D^* B_{1\theta} - \frac{im}{r} B_{1r} \right] .$$

Equation (1) can be written in the form

$$\rho \frac{\partial \vec{v}}{\partial t} + \rho (\vec{v} \cdot \nabla) \vec{v} = - \operatorname{grad} p + \frac{\vec{j} + \vec{B}}{c} , \quad (26)$$

which yields the linearized components

$$\rho_0 \sigma v_{1r} - 2 \rho_0 \Omega v_{1\theta} - \rho_1 r \Omega^2 = - D p_1 + \frac{1}{c} (j_{1\theta} B_{1z} + j_{1z} B_{1\theta}) ,$$

$$\rho_0 \sigma v_{1\theta} + 2 \rho_0 \Omega v_{1r} = - \frac{im}{r} p_1 + \frac{1}{c} (-j_{1r} B_{1\theta}) , \quad (27)$$

$$\rho_0 \sigma v_{1z} = - ik p_1 + \frac{1}{c} (-j_{1z} B_{1r}) .$$

When we substitute the expressions obtained above for ρ_1 , p_1 , j_0 , \vec{j}_1 and \vec{B}_1 , the three equations (27) become

$$\begin{aligned}
 v_{1r} - 2 \frac{\Omega}{\sigma} v_{1\theta} &= -\frac{i}{k} Dv_{1z} + \frac{r\Omega^2}{\sigma^2} \left[\text{div } \vec{v}_1 - 2 i k v_{1z} \right] \\
 &+ \frac{B_0^2}{4\pi\rho_0\sigma^2} \left[D(\text{div } v_1) - i k Dv_{1z} - k^2 v_{1r} \right], \\
 v_{1\theta} + 2 \frac{\Omega}{\sigma} v_{1r} &= \frac{im}{r} \left[\frac{c_s^2}{\sigma^2} \text{div } \vec{v}_1 + \frac{r\Omega^2}{\sigma^2} v_{1r} \right] \\
 &+ \frac{B_0^2}{4\pi\rho_0\sigma^2} \frac{im}{r} (\text{div } \vec{v}_1 - i k v_{1z}) - k^2 v_{1\theta} \quad (28) \\
 v_{1z} &= \frac{i k c_s^2}{\sigma^2} \text{div } \vec{v}_1 + \frac{i k r\Omega^2}{\sigma^2} v_{1r}
 \end{aligned}$$

The normal procedure now would be to solve the above differential equations (28) for the three components of \vec{v}_1 and apply the necessary boundary conditions at the perturbed surface of the plasma cylinder. It appears, however, that the variables are not separable in the first equation of (28), so it will probably be necessary to treat (28) as three simultaneous differential equations in three unknown variables $v_{1r}(r)$, $v_{1\theta}(r)$, $v_{1z}(r)$.

APPENDIX II

CONSTRUCTION OF THE EXPERIMENTAL APPARATUS

by

. Dale J. DeGeeter
Armour Research Foundation
Chicago, Illinois

ARMOUR RESEARCH FOUNDATION OF ILLINOIS INSTITUTE OF TECHNOLOGY

Appendix II

APPENDIX II

CONSTRUCTION OF THE EXPERIMENTAL APPARATUS

A. MAGNETIC FIELD

The magnetic field solenoid was energized during this period. Considerable effort was expended in bringing the operation to an acceptable level. A major problem was encountered in the operation of the triggered-gap switch in the magnetic field circuit.

The original switch, as described in a previous report, worked very well for the initial firings. Almost 100 percent operation was achieved for the first firings in the 500 to 4,000 volt region on the field capacitors. However, as the energy delivered increased, the copper became badly pitted from the energy dissipation at the surface of the electrodes. Molybdenum inserts were then made for the electrodes and a considerable improvement was noted. At above 2,500 volts on the capacitor bank the molybdenum also pitted but cleaning after several firings restores it.

In addition, breakdown between the central trigger wire and its surrounding electrode also occurred at the voltages necessary for satisfactory operation. The breakdown was traced to the considerable voltage across the 6BK4 tube at the operating current and the sputtered material retained on the teflon insulator. The problem was solved by the insertion of a side trigger in the gap.

A search coil was used to calibrate the magnetic field. Fig. 2 shows several of the waveforms observed. It should be pointed out that this is not a plot of the magnetic field since the signal from the coil pickup represents the rate of change of flux with time. This presents no special problem for after the calibration is made only the time is needed for computing the

magnetic field. A graph has been made plotting average values of the field against time and it will only be necessary to know when the plasmoid was fired to determine the magnetic field to an acceptable accuracy.

The method of arriving at the magnetic field curve for the various capacitor bank voltages can be illustrated using the voltage values from the curves in Fig. 2. The period of the oscillation can be read directly as 6 msec. The amplitude of the magnetic field can be calculated by substitution into the equation:

$$V = nAB\omega$$

where n = number of turns, A = average area of the loops, B = magnetic field, and ω = angular velocity. For air the magnetic field amplitudes at 3,000 and 4,000 volts are then calculated as:

$$H_{3000} \approx \frac{6.0 \times 10^4 (10^4)}{140 (6.28 \times 167)} \approx 4100^{+200} \text{ gauss}$$

$$H_{4000} \approx \frac{7.8}{6.0} (4100) \approx 5300^{+300} \text{ gauss}$$

These values correspond to the expected values from the coil design and are within the desired accuracy. The magnetic field can then be easily found at a time t , by evaluating the $\sin \omega t$, for the corresponding amplitude.

A check was then made on the magnetic field uniformity across the diameter of the chamber at the center of the solenoid. The variation was undetectable with the search coil oscilloscope combination and the field was established as being essentially homogeneous across the plasmoid chamber.

B. PLASMROID SOURCE ASSEMBLY

The button plasmoid source has been installed and connected as shown in Fig. 1. The capacitor with the 3-ball triggered gap switch is being used

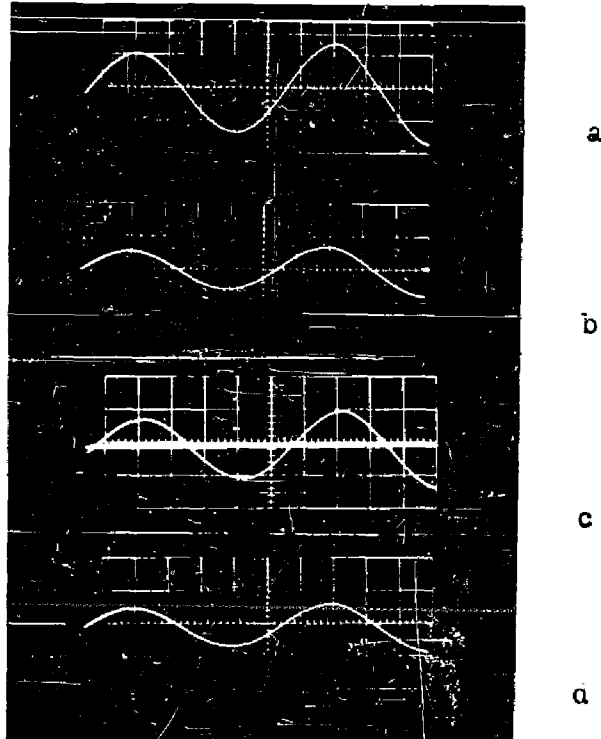


Fig. 2. The above traces show signals from a pickup coil in the magnetic field. The sweep speed was 1 m sec per cm, with time going from right to left, for all the traces. The vertical deflections and magnetic field capacitor bank voltages were as follows: a) 5 volts per cm and 4,000 volts, b) 10 volts per cm and 4,000 volts, c) 5 volts/cm and 3,000 volts, and d) 10 volts per cm and 4,000 volts.

for the button supply. The other capacitor is part of the pulse circuit to the center electrode and does not form a part of the actual discharge circuit. The leads from the capacitor are kept as close together as possible to minimize the inductance of the circuit. The terminating leads into the source are parallel copper strips with a surface for the leads from the button source to clamp to. These strips are wrapped with electrical tape to withstand the repulsive forces between the conductors. In addition, the copper leads were laminated to be flexible enough to rotate the source without uncoupling.

The button source has been fired and measurements made on the resulting discharge. Fig. 3 shows several oscilloscope traces of the voltage induced in a coil pickup from the discharge circuit. The quality of the pictures was limited by the oscilloscope operation at the high frequency encountered. A measurement of the curve over five cycles indicates there is an average period of about 0.3 μ sec. The current is considerably underdamped as was expected from impedance considerations. Again neglecting the slight damping, an approximation on the current through the source can be made by substituting appropriate values into the equation,

$$i_{\max} = V \sqrt{\frac{C}{L}} ,$$

Where V = initial capacitor voltage, C = capacitance of the capacitor, and L = inductance of the circuit. The first two of these are known quantities and the third can be calculated from the equation,

$$L = \frac{T^2}{4\pi^2 C}$$

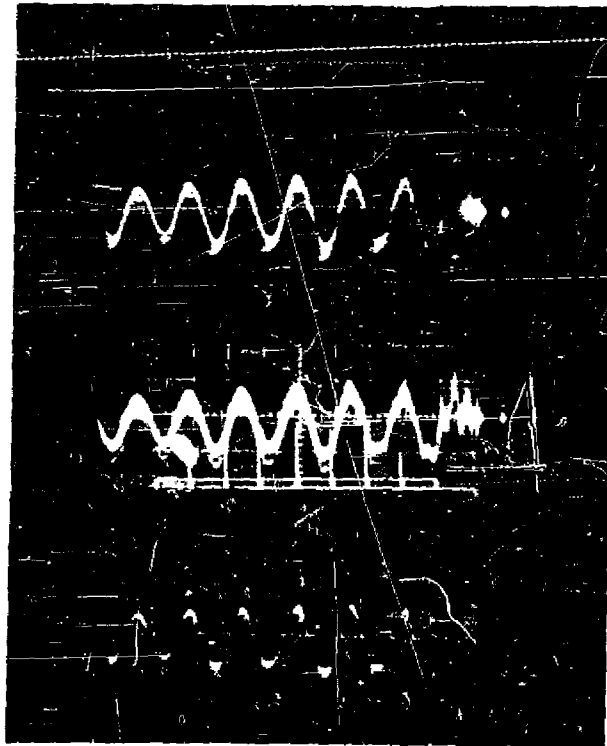


Fig. 3. The above traces show signals from a pickup coil in the plasmoid discharge circuit. The sweep speed was 0.2μ sec per cm, with time going from right to left.

If a discharge through the button source with 25 Kv on the capacitors is considered the current amplitude can be calculated as,

$$i_{\max} = V \sqrt{\frac{C}{L}} = \frac{2\pi VC}{T}$$

$$i_{\max} = \frac{2\pi(25,000 \times .025 \times 10^{-6})}{.30 \times 10^{-6}} \approx 13,000 \text{ amperes}$$

The triggered-gap switch used in the plasmoid source circuit has been found to operate very well. In the course of placing the switch in operation two critical points were noted. First, the distance between electrodes had to be precisely set to obtain a proper breakdown sequence between the spheres, and secondly, a small resistance had to be included in the pulse electrode lead to damp out oscillations occurring in this circuit during the discharge. In addition it has been found that the circuit is a good transmitter of RF energy which causes some interference with other measuring equipment. Some of this has been eliminated, however, a shield will probably be added in the near future to reduce this undesirable characteristic.

C. ELECTRONIC CIRCUITRY

A change has been made in the method of triggering the time delay due to the presence of jitter in the low voltage switch triggering the magnetic field. It was not practical to continue work on removing the jitter since an alternate method was readily available. Instead of starting the time delay from the pushbutton triggering the magnetic field, a pickup coil on the magnetic field circuit will be used to accomplish the time delay triggering. Then, if there is jitter in the switch, it will not affect the time interval between the magnetic field and plasmoid firing.

The time interval can then be set and duplicated on subsequent firings to the accuracy required.

APPENDIX III

EXPERIMENTAL RESULTS

by

Dale J. DeGeeter
Armour Research Foundation
Chicago, Illinois

ARMOUR RESEARCH FOUNDATION OF ILLINOIS INSTITUTE OF TECHNOLOGY

Appendix III

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APPENDIX III

EXPERIMENTAL RESULTS

In the course of the final developmental work on the plasmoid apparatus many preliminary firings were made and several were recorded by photographic methods. Figs. 4, 5, 6, and 7 are time-exposure pictures of plasmoids taken with a conventional photographic camera.

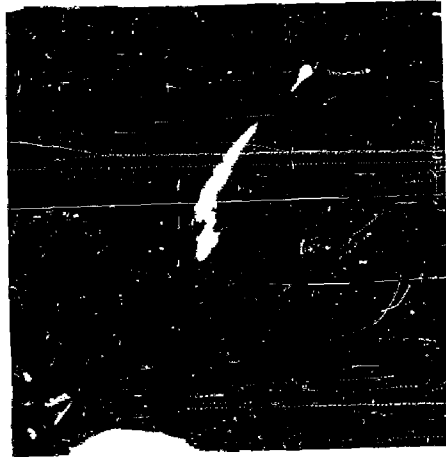
Considerable experience was gained in photographing the plasmoids. The first photographs failed to show anything beside the arc from the source. This was not unexpected and with constant improvement of photographic techniques and film a set of photographs of good quality was obtained. The final improvement was made by using Kodak Royal-X panchromatic film. This is the fastest commercial film made by Kodak and its application caused considerable improvement in the pictures. It appears that the photographing of this extremely high speed event at the low light levels involved could be within the reciprocity failure region of the preceding films used.

There was considerable reflection within the container detracting from the photograph quality. To reduce this the glass container was given an "Aquadag" suspension coating and the metal parts were covered with black neoprene rubber. The picture of the camera, which can be seen superimposed in the background, was introduced by the reflection from the glass plate on top of the vacuum chamber. If necessary, this image can be removed by masking.

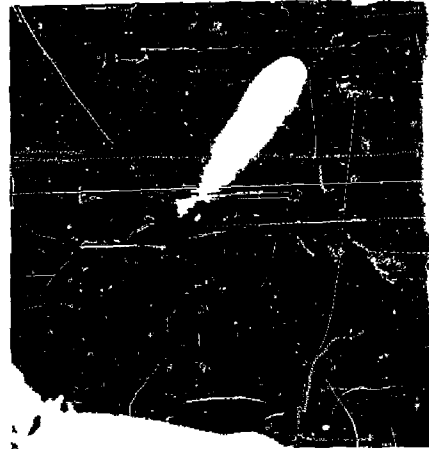
A discussion of the photographs is especially interesting when one notes the differences between several of the plasmoids of Fig. 4. The



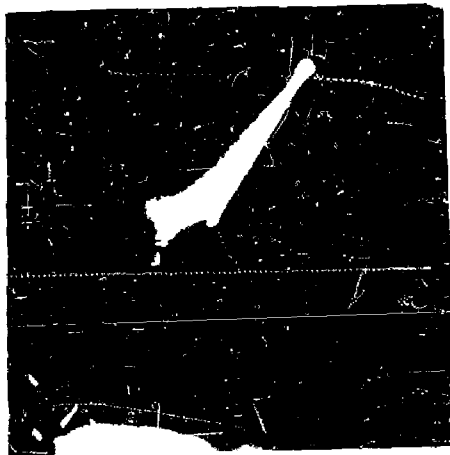
(a)



(c)



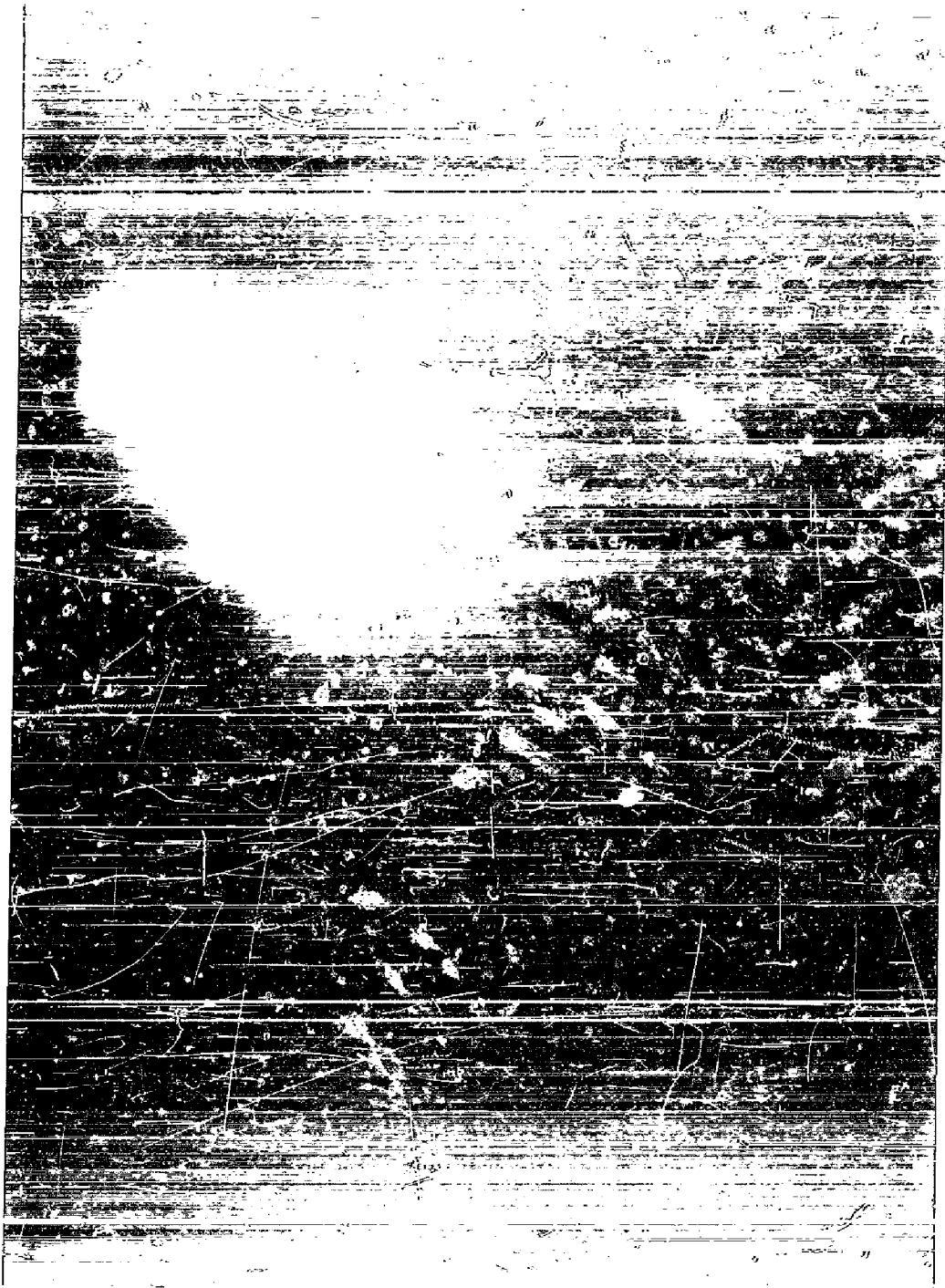
(d)



(e)



Fig. . Time-exposure photographs of a plasmoid projected across the vacuum chamber at different magnetic field values.



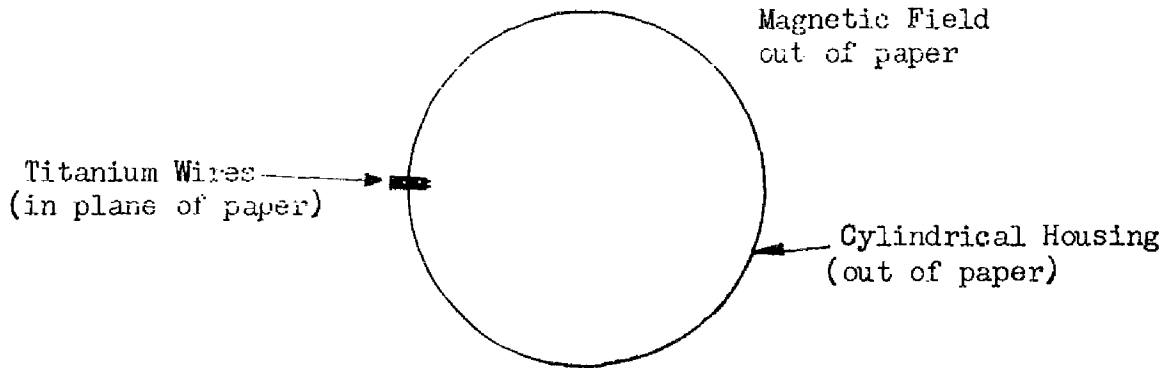


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plasmoids were fired across the chamber with a geometry as sketched below.



The pressure in the chamber was about 10^{-3} mm and a magnetic field of differing magnitudes was present for each firing. A probe is directly opposite the discharge and the interaction can be seen in the pictures.

The amplitude of the current through the source was about 14,000 amperes.

Figures 4(d), 4(e), and 4(f) show the plasmoid traveling in a relatively straight trajectory. The difference in pinching of the plasma indicates that 4(d) was fired at a low magnetic field strength. Our observations of the discharge without the magnetic field as in Fig. 5 confirm the increased contracting action in the arc with increasing field as reported by Bostick¹. Fig. 6 is an enlargement of one of the straight plasmoids.

It is interesting to note the interaction of this plasmoid with the probe. Streams of particles scattered from the probe are observed especially when the plasmoid trajectory tends to graze the probe on one side. It even appears that there is an elastic type scattering present. On the other hand, if the collision is head on into the probe the scattering takes on more of

¹ W. H. Bostick, University of California Radiation Laboratory Report UCRL-4595 (1956) "Experimental Study of Ionized Matter Projected Across Across a Magnetic Field".

an inelastic appearance. No attempt will be made at this time to interpret this since further experiments and more data will be needed.

The occurrence of plasma with considerably curved trajectories has been recorded. Fig. 7 is an enlargement of one of the curved plasmas. Again the curved trajectory has been reported by Bostick² with pictures similar to those in Fig. 4. Future work with this variety will be continued to gain a knowledge of their properties and an analysis of the phenomena.

²W. H. Bostick, University of California Radiation Laboratory Report UCRL-4595 (1956) "Experimental Study of Ionized Matter Projected Across a Magnetic Field".

APPENDIX IV

MEASUREMENT OF THE MAGNETIC FIELD IN A PLASMOID
BY MEANS OF GYRORESONANCE WITH MICROWAVE BEAMS

by

R. Lee Watkins
Armour Research Foundation
Chicago, Illinois

ARMOUR RESEARCH FOUNDATION OF ILLINOIS INSTITUTE OF TECHNOLOGY

APPENDIX IV

MEASUREMENT OF THE MAGNETIC FIELD IN A PLASMOID BY MEANS OF GYRORESONANCE WITH MICROWAVE BEAMS

By the application of the phenomena of gyroresonance of the electrons in an ionized gas there is the possibility of determining the magnitude of the magnetic field that exists within the plasmoid as it travels through space.

As is well known electrons in a plasma which is in a magnetic field will oscillate with a frequency given by,

$$\omega_b = - \frac{eH}{mc} , \quad (1)$$

where $\frac{e}{m}$ is the charge to mass ratio of the electron,
H is the magnitude of the magnetic field,
c is the velocity of light, and
 ω_b is the angular frequency of oscillation.

An electromagnetic wave propagating through the medium will experience an absorption as well as a phase change when its frequency is equal to the frequency ω_b . The magnetic field H may be calculated therefore if the resonant frequency is known. If a plasmoid has the shape postulated by Bostick¹ with internal currents flowing thereby producing a magnetic field it would seem logical that electrons in their field would gyrate. The interactions between these gyrating electrons to microwaves will produce an absorption of the microwaves which can be measured by reflection or transmission experiments.

¹W. H. Bostick, Phys. Rev. 104, 292, (1956).

The experimental arrangement is shown in Fig. 8. The plasmoid will be fired across a continuous microwave beam and at the point in time when an absorption is observed at the receiving horn one knows that the magnetic field in the plasmoid has gone through a specified value. One has assumed in the above case that the plasmoid will have a larger magnetic field at the time it is fired and that it passes through the gyroresonance frequency while it is in the microwave beam. It is also assumed that the magnetic field is reasonably uniform over the plasmoid. If the magnetic field is not reasonably uniform over its area then a continuous function will be observed at the receiving horn which is an indication of the homogeneity of the magnetic field.

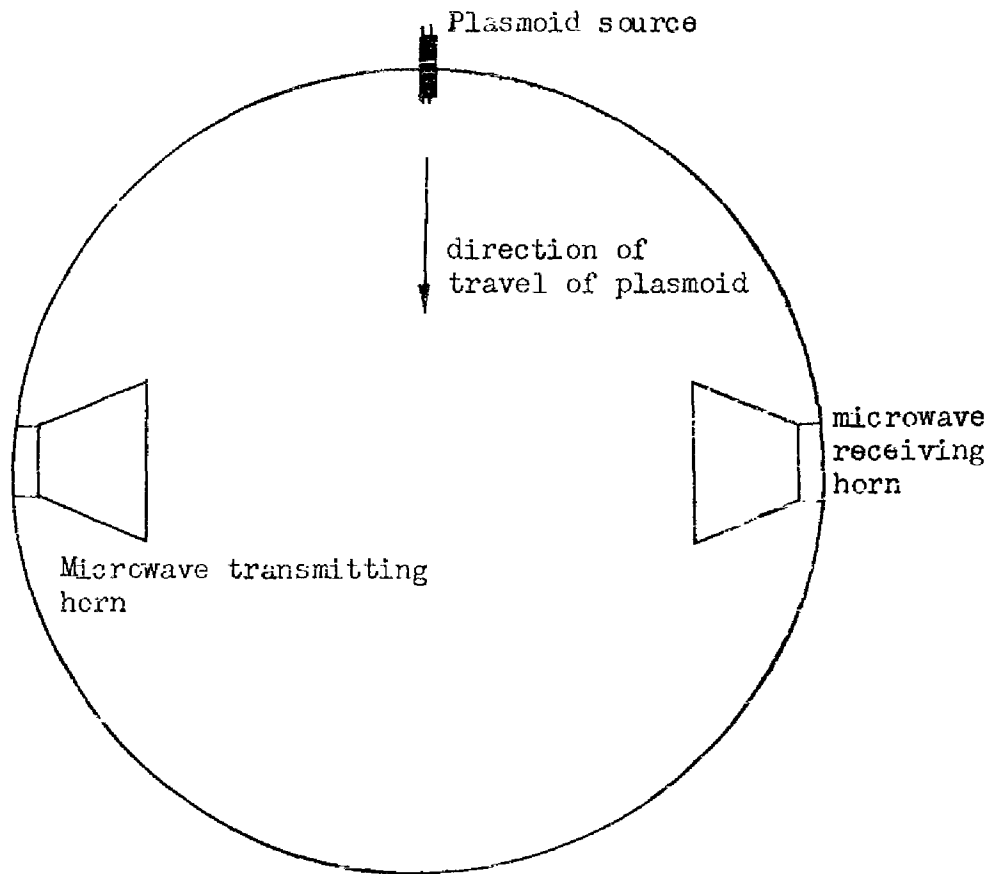


Fig. 8 Microwave Measurements Configuration