were accounted for fully. Since the theory contained no adjustable constants, it is felt that the agreement is encouraging.

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Structure of a Large-Radius Pinch Discharge

Robert G. Jahn* and Woldemar von Jaskowsky†
Princeton University, Princeton, N. J.

A large-radius pinch discharge produces a series of cylindrically symmetric, inwardly propagating current sheets and associated magnetic fields in a form convenient for detailed study of the $j \times B$ interactions basic to all schemes of electromagnetic gas acceleration. The discharge is examined by streak and Kerr cell photography, magnetic probes, spectroscopy, microwaves, and terminal measurements of current and voltage fluctuations, in order to determine the detailed distribution of the currents and fields as functions of radius and time. The initiation of the main discharge in a uniform peripheral ring is found to be primarily an inductive effect, conditioned somewhat by the presence of the adjacent insulator surface. Spectrograms of discharges in argon, nitrogen, and helium show singly and doubly ionized species indicating that particles of energy in excess of 25 ev are participating in the breakdown. A precursor front is observed to propagate ahead of the first current sheet and is identified tentatively as a gasdynamic shock. Another precursor, propagating many times faster, preionizes the gas slightly, prior to the arrival of the first current sheet.

I. Introduction

THE research described herein is directed toward an understanding of the initiation, development, and dynamic progress of the current sheets and associated magnetic fronts in a large-radius pinch discharge. The ultimate application is toward the efficient acceleration of an ambient body of gas for propulsion, but the present experiments are confined to the details of the discharge itself, with no attempt made to exhaust the plasma to generate thrust. The central apparatus is an aluminum discharge chamber with 8-in.-diam plane electrodes separated by a 2-in. gap of test gas. The discharge is driven by a circular bank of 15 1.0-μf capacitors charged to 10,000 v, ringing down through a low inductance circuit via a special gas-triggered switch described in detail elsewhere.[1] Figures 1 and 2 show a schematic drawing and a photograph of the circuit assembly.

The terminal electrical characteristics of the discharge are monitored by a current-measuring Rogowski coil encircling the switch column and a voltage divider applied across the main electrodes. From these it is found that the peak current in the discharge is about 200,000 amps, that the resonant frequency is about 250 kc, and that the total voltage developed across the chamber after breakdown is about 10% of that across the capacitors. It also is possible to infer the gross characteristics of the current distributions within the chamber as functions of time after breakdown.

The progress of the luminous patterns that develop within the chamber during the discharge are observed by rotating mirror streak photographs taken along a diameter of the chamber and by single-frame Kerr cell photographs taken at selected times. The details of the current density distributions are determined by small magnetic probes positioned at various radii inside the discharge chamber. Spectroscopic techniques provide information about the existence and development of various atomic and ionic species in the discharge, and 8- and 4-mm microwave probes monitor the development of the free electron density patterns. The

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* Assistant Professor of Aeronautical Engineering. Member AIAA.

† Research Staff Member.

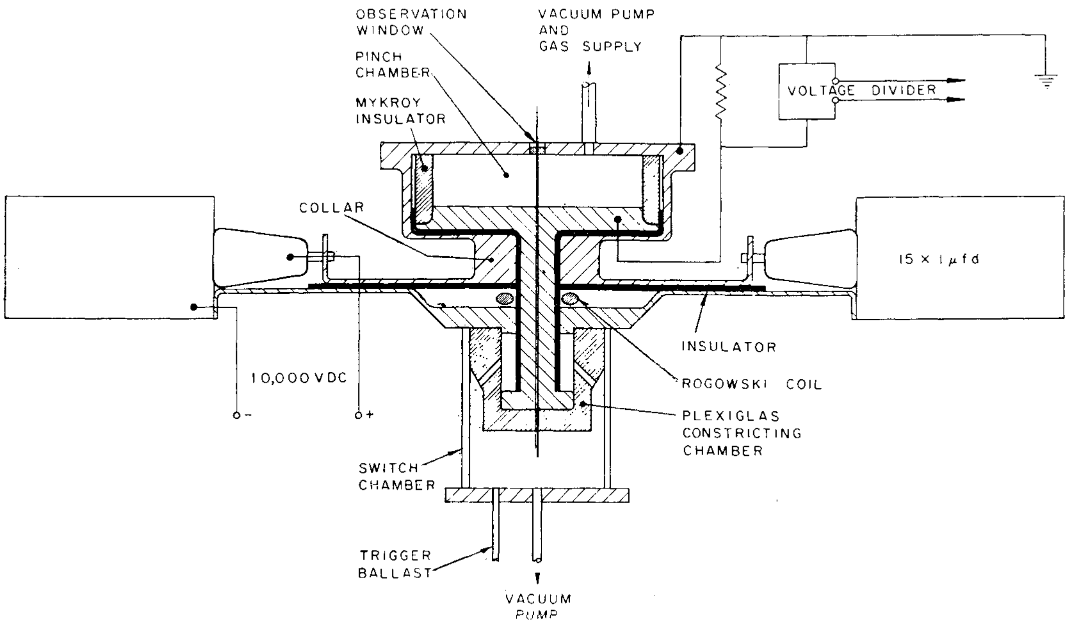


Fig. 1 Plasma pinch apparatus (schematic).

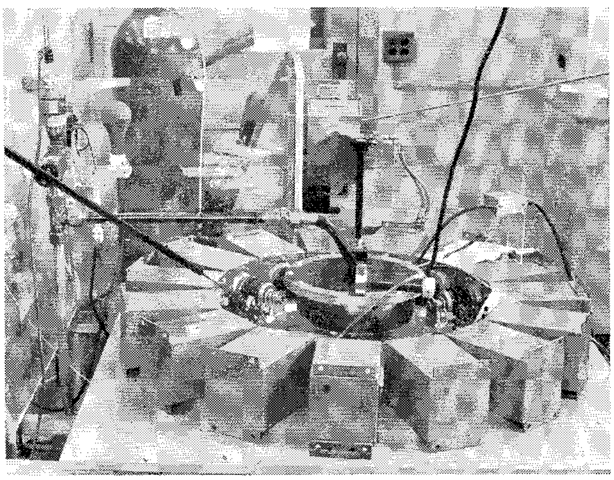


Fig. 2 View of plasma pinch apparatus.

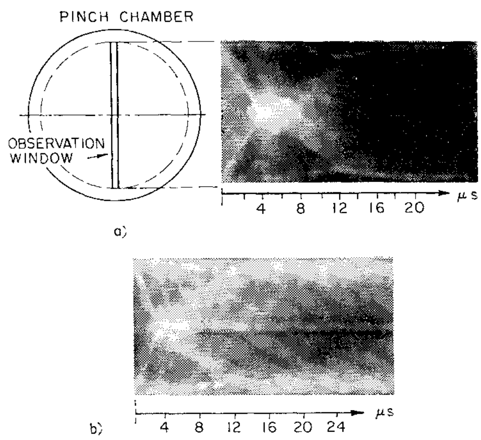


Fig. 3 Streak photographs of discharges in argon at 47 μ initial pressure: a) typical record; b) higher current discharge, showing luminous percursor.

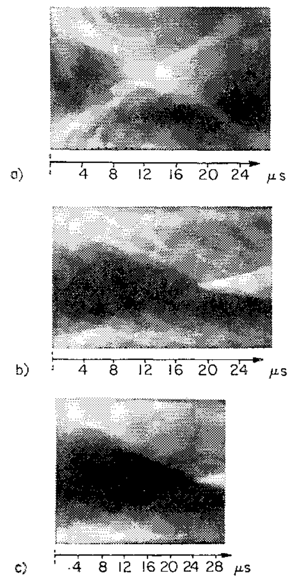


Fig. 4 Streak photographs of discharges in argon: a) 170 μ; b) 660 μ; c) 1000 μ.

results of these and other measurements and the conclusions drawn from them constitute the body of this paper.

II. Luminous Fronts

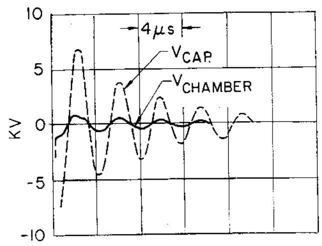
Figure 3a displays a typical streak photograph taken of a discharge in argon at 47 μ ambient pressure. The breakdown is seen to initiate as a peripheral ring at the outer edge of the electrodes and then to accelerate inward. Subsequent discharges, occurring at the second, third, and later voltage maxima of the capacitor ring-down pattern, also are established at the outer edge of the electrodes and follow the primary luminous front in toward the center. At this pressure, the luminous fronts propagate so rapidly that each travels more than one-half the total radius before the next begins at the outer edge.

In discharges at higher pressures, the fronts travel less rapidly and hence are spaced more closely. At 1 mm, for example, they appear to coalesce near their inception and then propagate inward as one composite front. Figure 4 shows typical streak photographs obtained for argon at 170 μ, 660 μ, and 1 mm. The speed of the leading luminous front has been found to vary approximately as the inverse square root of the ambient gas density over a range of 20 μ to 10 mm for argon, nitrogen, and helium.

III. Current Distributions

The most pressing question raised by the phenomenological observations of the progress of the luminous fronts is whether they actually carry current with them in toward the center of the discharge. Measurements of terminal voltage seem to indicate that they do not, for at no time during the dis-

Fig. 5 Voltage across capacitors and discharge chamber.



charge does more than 10% of the capacitor voltage appear across the electrodes, thus implying that the discharge departs little from its minimum inductance configuration at breakdown, namely, a peripheral ring of uniform current density (cf., Fig. 5). For purposes of comparison, the circuit may be discharged with the chamber shorted by various inductance geometries. For example, an 8-in.-diam aluminum ring that shorts the two electrodes at their periphery, adjacent to the insulator, simulates the minimum inductance configuration that the discharge possibly could assume. Alternatively, a 1-in.-diam solid aluminum post placed at the center of the chamber shorts the electrodes in a comparatively high inductance configuration and thereby simulates a discharge that has become localized at the center. The frequency and the voltage amplitude of an actual gas discharge are found to be very close to those obtained with the pinch chamber shorted by the 8-in.-diam ring and drastically different from those obtained with the shorting center post. The implication is thus that the bulk of the discharge current remains near the outer wall of the chamber, throughout the entire cycle, even though the luminous fronts propagate toward the center.

As an independent experimental check of this effect, 5-in.-diam circular areas in the center of both the upper and lower electrodes were insulated by thin sheets of Mylar. The streak pictures of the pinch discharge under this situation were compared with streak pictures of the discharges without the insulation on the central parts of the electrodes. The luminous fronts were found in both cases to travel inward with exactly the same velocity profiles over the entire radial contraction. The development of all other qualitative details of the two streak pictures was identical. Thus, the center portions of the electrodes appear to transmit no current to the discharge.

To obtain more information about the details of the luminous fronts, small magnetic probes[2] were introduced at various radial positions within the discharge. These are constructed of 8 turns of 0.25-mm enameled wire, each of 1.9- × 1.6-mm cross section, enclosed in a 4.3-mm-o.d. pyrex tube, inserted radially through the side wall of the insulator. Figure 6 shows the response $(\partial B/\partial t)(t)$ and integrated response $B(t)$ of one such probe located at radii of 3.0 and 1.5 in. The series of sharp spikes on the $\partial B/\partial t$ records immediately indicates that, contrary to the suspicion raised by the terminal voltage measurements, a succession of discrete current-carrying fronts is propagating well into the center of the chamber.

The apparent contradiction between the voltage divider and magnetic probe data seems to imply that each inwardly propagating current sheet becomes uncoupled from the ex-

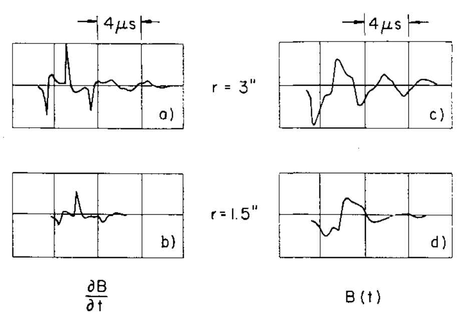


Fig. 6 Magnetic probe responses to discharge.

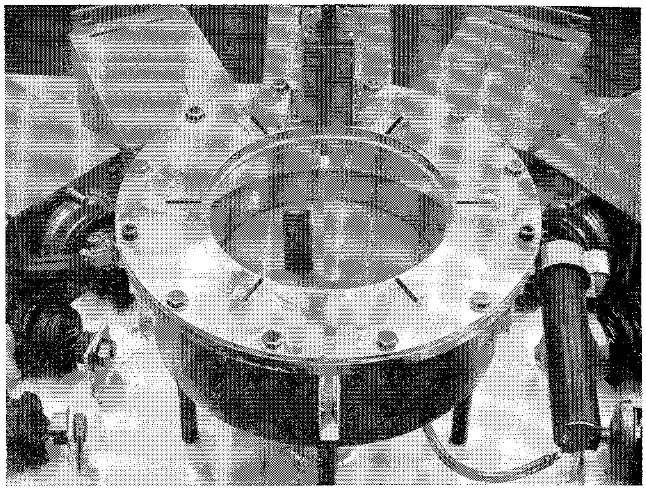


Fig. 7 View of plasma pinch apparatus with glass electrode section.

ternal circuit when a new sheet is formed outside of it, after which it carries only interior, circulating currents, divorced from the current fluctuations in the outer circuit. For example, the current carried in any one sheet is found never to reverse. The first sheet carries the bulk of the circuit current for the first half-cycle. The reversed current of the second half-cycle appears mainly in the second sheet, while the first retains some small fraction of its original component, trapped within itself. The onset of the third half-cycle generates a third sheet carrying that re-reversed current, etc. The appearance of trapped interior currents implies the existence of corresponding trapped fields, the combination of which must participate in the composite acceleration process for the entire wave pattern. Similar effects have been observed by Lovberg[3] and others, in different discharge geometries.

IV. Azimuthal Stability

In interpreting the streak photographs as in the foregoing, one is assuming that the diametral slot in the electrode permits a representative sectional view of a cylindrically symmetric event, without itself distorting it in any way. To check this, an upper electrode with three diametral slots at angles of 60° to each other was constructed, and single-frame Kerr cell photographs were taken through it at various selected times. These supported the assumption of cylindrical symmetry.

Much more conclusive evidence was obtained with a radically different upper electrode, however. The observed indifference of the discharge to insulation of the center portions of the electrodes mentioned earlier permits the use of electrodes that are solid aluminum only for the outer 1 in. of their radii; the remainder are pyrex plates (Fig. 7). Almost the entire interior of the chamber thus is made visible to a Kerr cell camera. The photographs obtained through such electrodes clearly illustrate the detachment of the current sheets from the external circuit and demonstrate the extent of their cylindrical symmetry (see Figs. 8–10).

One interesting property rendered accessible by this technique is the degree of azimuthal stability prevailing in the plasma rings. It is anticipated that such sheets would be susceptible to a Rayleigh-Taylor type of instability, and, indeed, small characteristic irregularities are seen to arise at random positions on the luminous rings. In no case, however, have these been observed to develop far enough to impair the overall cylindrical uniformity of the fronts.

In a similar way, the sensitivity of the discharge patterns to the symmetry of the external circuit and capacitor bank has been studied and found to be negligible. In one extreme experiment, 11 of the 15 capacitors were removed, leaving

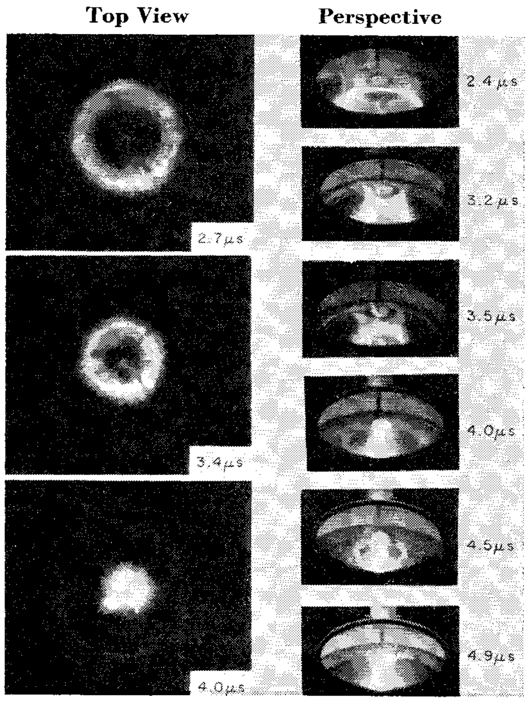


Fig. 8 Kerr cell photographs of pinch discharge in argon at 47 μ initial pressure.

four adjacent capacitors, all on one side of the circular plates leading to the chamber electrode. The discharges remained cylindrical and uniform, reflecting none of the severe assymmetry in the external current pattern. A similar insensitivity of the symmetry of the discharge to the level of applied voltage from a full bank of capacitors was found down to 5 kv, where the luminous patterns still could be distinguished.

V. Precursor Fronts

In Fig. 3a, which displays the streak photograph of a discharge through 47 μ of argon, an additional feature of interest is the appearance of intense luminosity at the center of the chamber in advance of the arrival of the first luminous front. The suspicion is that another signal or front, invisible on the photograph, precedes the luminous front into the center. Only after collapsing on itself there does this precursor manifest itself by exciting the gas at the center of the chamber to perceptible brightness.

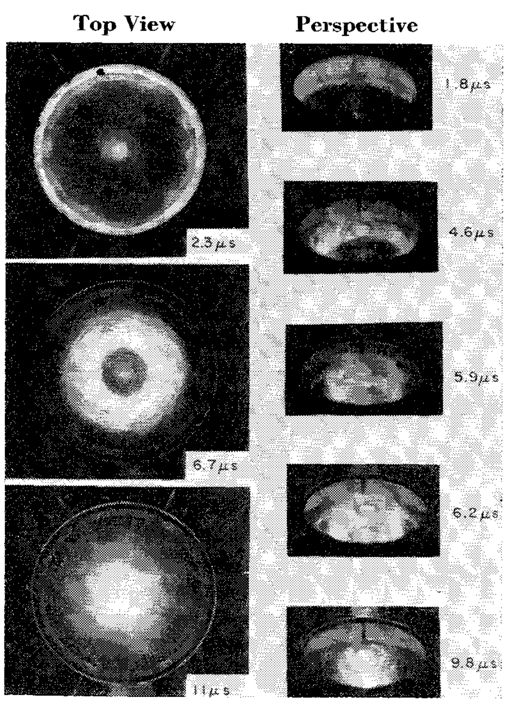


Fig. 9 Kerr cell photographs of pinch discharge in argon at 170 μ initial pressure.

Attempts were made to locate this front by intercepting it with a variety of obstacles, such as glass and nylon posts placed at various radial positions in the chamber, but no unambiguous indications of its reflection from such obstacles was found (see below). However, during the course of an empirical study of characteristics of the gas-triggered switch,[1] it was possible to increase the peak current of the main discharge by about 15% for one or two isolated shots. In these, the suspected signal became visible over its entire inward excursion. Figure 3b shows one of the few streak photographs obtained in this way at 47 μ of argon.

No manifestation of this precursor front is found on the magnetic probe records, indicating that, unlike the other luminous fronts, it carries no significant part of the discharge current. It is tempting to guess that it may be a gasdynamic shock front, driven by the piston action of the first current sheet accelerated by its own magnetic field. If so, it propagates with a nearly constant Mach number of about 120

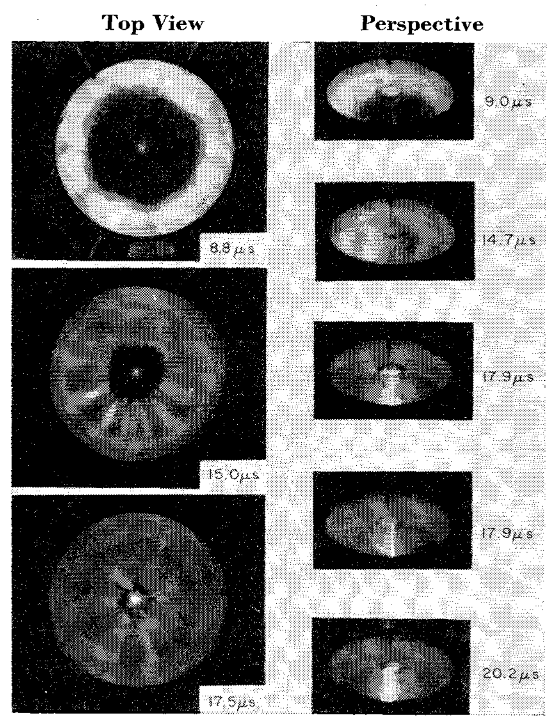


Fig. 10 Kerr cell photographs of pinch discharge in argon at 660 μ initial pressure.

at this pressure. More important, it implies that the current-sheet piston is accelerating efficiently the body of gas ahead of it. Precursors similar to this have been identified in other discharge geometries.[4]

Evaluation of the "sweeping efficiency" of the current sheets is particularly important from a propulsion standpoint. Unfortunately, there seems to be no appropriate total density probing technique of adequate time resolution for this low-density range, which could confirm the shock wave model postulated in the foregoing. As a substitute, small obstacles have been placed in the chamber, and the bow waves and other disturbances generated by them in the discharge flow have been observed by the Kerr cell photography (see Figs. 11 and 12). A wide range of bow shock angles is observed, but lack of information about local sound speeds prevents unambiguous assignment of local flow velocities.

An unexpected dividend of these obstacle studies is the appearance of a uniform glow around the entire periphery of the obstacle long before the arrival of either the main luminous front or the anticipated gasdynamic shock. It is speculated that this phenomenon is related to a fast electron-producing precursor also found in our microwave studies. The microwave experiments originally were undertaken in the hope of mapping free electron density profiles through the current sheets, but both 8- and 4-mm waves were found to be reflected totally by the main current-carrying regions of the discharge. However, simple transverse probes,[5] looking through the glass portion of the electrode at various radial positions, did reveal the inward propagation of a very fast precursor front. At an initial pressure of 47 μ, for example, this front reaches the center of the chamber in about 0.5 sec, implying a velocity of about 2×10^5 m/sec, nearly an order of magnitude faster than the luminous front. These precursors produce free electron densities $\sim 10^{13}$ cm^{-3} which, if derived from the ambient gas, imply degrees of ionization $\sim 1\%$. It is possible that they correspond to the electron-driven precursors found in some electric shock tube work.[6]

VI. Spectral Characteristics

Streak photographs of the discharge taken with Ektachrome film[7] show well-defined regions of various characteristic colors and encourage detailed spectroscopic study of the corresponding regimes of the luminous gas. Stigmatic spectrograms along the diameter of the pinch chamber have been obtained for argon, helium, and nitrogen at initial pressures from 20 μ to 10 mm. Line spectra of the test gas and of certain characteristic impurities up to the second degree of ionization are observed, particularly near the periphery of the chamber at the time of inception, and at the center at the time of constriction. Although the latter possibly may reflect a thermal process, the former must imply the presence of free electrons with energies above 25 ev at the time of breakdown. These energies are comparable to the voltage across the electrodes multiplied by the ratio of electron mean free path to the electrode gap, that is, the typical energy that an electron acquires from the electric field between collisions. Bremms continuum is observed, well confined to the center of the discharge at the time of tight constriction, indicating high electron densities in this region.

VII. Insulator Experiments

It seems important to determine the role played by the insulator surface separating the electrodes at the periphery of the chamber, in the initiation of the breakdown and the subsequent inward acceleration of the plasma. In particular, the relative importance of two specific insulator mechanisms to concomitant electrodynamic ones needs to be resolved:

1) Is the observed mode of initial breakdown—in a uniform peripheral ring—entirely attributable to inductive processes (skin effect), or is this the preferred location because it is adjacent to the insulator surface? The relevance of such insulator surfaces to more conventional high voltage breakdown is well known,[8] and similar mechanisms may carry over to the very-high-frequency impulsive discharges involved here.

2) Is the inward acceleration of the plasma sheet driven solely by the magnetogasdynamic forces, or is it mainly a consequence of a thermal expansion of the plasma away from this fixed wall? Rudimentary calculations indicate that, for the particular electrical and geometrical parameters prevailing, the magnetic forces and pressure forces may indeed be comparable, although precise evaluation of the latter is precluded by uncertainties in the state of the gas involved in the discharge.

To illuminate these situations, several series of experiments were performed with various additional insulator surfaces purposely established in the chamber. In one series, a Plexiglas ring, 6-in.-o.d. $\times$ $\frac{1}{8}$-in. wall, was inserted in the chamber coaxial with the original insulator surface and in contact with the electrodes (see Fig. 13a). A series of streak photographs was taken of discharges in argon at pressures of 170 μ, 660 μ, and 1 mm, all at 10,000 v and 15 μf, to determine whether the two additional insulator surfaces also would generate discharges along themselves. To check whether the specific insulator material or its radial position were critical to the experiment, a second series of discharges was studied using a 5-in.-o.d. $\times$ $\frac{1}{4}$-in. wall glass ring in place of the Plexiglas. The behavior of the discharge in both situations was somewhat equivocal. In all cases a strong discharge was maintained at the outermost (Mykroy) surface, of the same type seen in the empty chamber shots. The outer surface of the inserted rings seldom generated any significant discharges, but the inner surface did on some occasions, par-

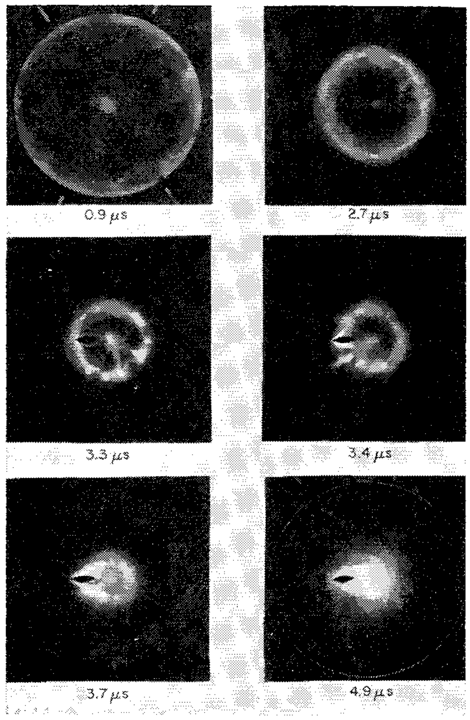


Fig. 11 Kerr cell photographs of pinch discharge in 47 μ argon with obstacle in chamber.

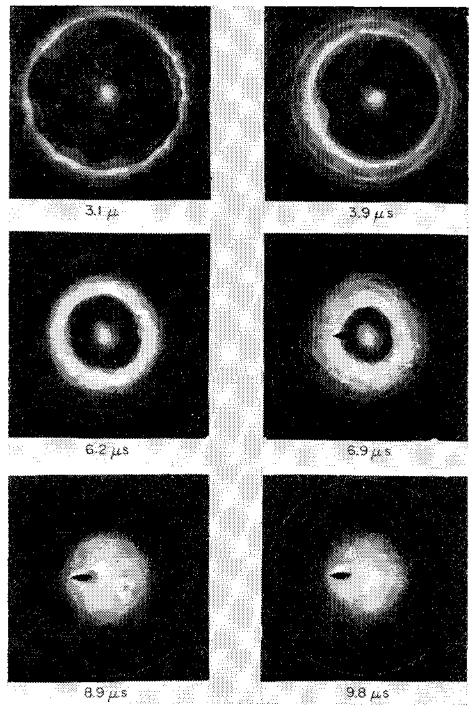


Fig. 12 Kerr cell photographs of pinch discharge in 170 μ argon with obstacle in chamber.

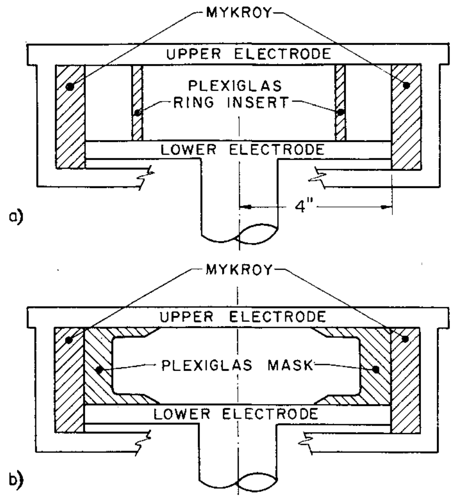


Fig. 13 Arrangement of insulating inserts in discharge chamber: a) ring insert; b) mask insert.

ticularly at the lower pressures. These latter, once established, pinched toward the center with nearly the same speed as the main discharges from the outside. The conclusion would seem to be that the insulator surface does establish a favorable location for the discharge, but that the inductive effects remain paramount in selecting the largest diameter for the bulk of the current. The lack of participation of the outer surface of the ring inserts may result from the unfavorable direction of the magnetic pressure there, which tends to restrain the current sheet from propagating away from the surface.

The "insulator effect" was pursued a bit further by inserting a hollow cylindrical Plexiglas mask into the chamber, where it effectively covered the outer 2 in. of both electrode surfaces (see Fig. 13b). It thus offered the discharge the alternatives of a path directly across the chamber at a 2-in. radius, or a path three times longer along the insulator surfaces, out to a $3\frac{1}{4}$-in. radius where the inductance would be less. Without exception, the path chosen was that directly across the chamber from the outermost exposed surface of the electrodes. Once formed, these discharges also were capable of pinching themselves in toward the center of the chamber and showed no tendency to expand outward into the insulator cavity. Two conclusions seem justified. First, neither the mechanisms of inductance minimization nor the previously demonstrated influence of an insulator surface are strong enough to cause the discharge to take the longer paths for this particular geometry. Second, the magnetogasdynamic forces are capable of pinching the discharge, even in the absence of a nearby wall. The lack of any discernible outward motion of the plasma from its ring of inception may be an indication of the relative insignificance of thermal expansion contributions to the acceleration, contrary to the situation in other discharge geometries.[9]

VIII. Conclusions

The experiments described in the foregoing have confirmed that a series of discrete, cylindrical current sheets are generated in this large-diameter pinch discharge and that these propagate inward, one after the other, with nearly the same speeds for a given ambient density. At any one time, only the outermost sheet is coupled strongly to the external circuit; the others carry "trapped" currents and are separated by corresponding regions of trapped magnetic fields. At least two distinct precursors propagate ahead of the first luminous front. One, slightly faster than the luminous front, appears to be a gasdynamic shock; the other, many times faster, generates free electron densities of the order of 1% of the ambient density.

Thus, the familiar $j \times B$ interaction, basic to any electromagnetic mode of gas acceleration, appears to have a rather complex manifestation under the circumstances of this discharge, and the detailed mechanism by which the external circuit energy is converted to directed motion of the body of gas requires further study.

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