Ejection of a Pinched Plasma from an Axial Orifice

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The ejection of an argon plasma produced in a large-radius pinch discharge chamber from an axial orifice in one electrode is studied photographically, and with magnetic probes. The development of the discharge within the chamber is found to be disturbed very little by the presence of the large aperture, but a luminous front and current sheet are observed to diffract radially and axially outward through the orifice, establishing an exhaust plume that embodies large current densities and magnetic fields. The intense plasma column created by the radial pinch within the chamber also expands axially out through the orifice, eventually overtaking and piercing through the previously ejected diffracted front. In some cases the velocity of this axial expansion exceeds that of the prior interior radial motion, indicating significant recovery of the thermal energy resident in the pinch column.

1. Introduction

Any pulsed plasma accelerator must accomplish a sequence of three physical operations. First, a sufficiently impermeable current sheet must be established in a proper geometric location; then, this current sheet must be accelerated stably by its own magnetic field into an ambient body of gas; and finally, the accelerated and heated body of gas must be ejected from the acceleration chamber. The first two processes have been studied in considerable detail for various accelerator geometries.[1-4] The ejection process seems to have received comparatively little systematic study, although a variety of curious phenomenological observations have been reported in connection with the detachment of the plasma from the muzzle of coaxial guns and pinch engines.[5-7]

The importance of the ejection process to the over-all efficiency of the accelerator is evident enough, but reduction of the problem to its essential mechanisms is not entirely straightforward. At least three general questions can be defined: 1) to what extent does the existence of the exhaust orifice influence the development of the discharge within the acceleration chamber? 2) to what extent may random thermal energy resident in the plasma be recovered in directed motion upon ejection through the orifice? and 3) to what extent are current densities and magnetic fields present in and around the exhaust plume, thereby extending the acceleration process, or perhaps impeding the detachment of the plasma from the orifice? This subdivision of the problem becomes less clear-cut, however, when these questions are cast against the myriad of possible orifice sizes and shapes and interior discharge characteristics.

2. Apparatus and Technique

In an effort to acquire some information on these questions, a linear pinch discharge device, 5-in. × 2-in. gap, shown in Fig. 1, and described in detail in an earlier paper[8] is equipped with an assortment of interchangeable outer electrodes, each containing a centered orifice of a particular diameter and profile. The discharge is driven by a bank of 15 — 1 μfarad capacitors charged to 10 kv that ring down at about 400 kc, delivering about 300,000 amps peak current. The plasma generated by the radial implosion of the discharge current sheet is allowed to exhaust axially through the orifice into a large, cylindrical pyrex vessel, coaxial with the pinch chamber and orifice, and maintained at the same ambient pressure as the interior of the pinch chamber. The development of the exhaust plume, and the preceding development of the discharge within the chamber near the orifice, are studied by Kerr-cell and streak photographs and by a series of magnetic probe traverses of the same regions, for ambient pressures of 30, 120, 480, and 1920 μ of argon.

3. Effect of Aperture Size and Profile

To determine the optimum orifice configuration on which to conduct detailed experiments, the exhaust plumes emerging from various diameter apertures were first surveyed photographically. Straight-bore orifices of $\frac{3}{8}$-, $\frac{3}{4}$-, $1\frac{1}{2}$-, 2-, 3-, and 4-in. diam × $\frac{1}{2}$-in. long were allowed to discharge into a 6-in. diam × 24-in. long pyrex exhaust tank, through which streak photographs mapping the axial progression of the exhaust luminosity along the centerline, and radial view Kerr-cell photographs displaying the complete geometry of the luminous plume at selected times, were obtained. A typical streak photograph is shown in Fig. 2. In each case, the main luminous leading edge of the exhaust is observed to emerge with a particular initial speed, and then to decelerate at a rate characteristic of the hole size and of the ambient pressure. Figure 3 summarizes the observed behavior of these trajectories for discharges in 120 μ argon, which is qualitatively similar to that observed for the other pressures. For the smaller size holes, the initial ejection speeds are nearly the same, but the persistence of the leading edge speed downstream of the orifice clearly improves with increasing hole diameter.

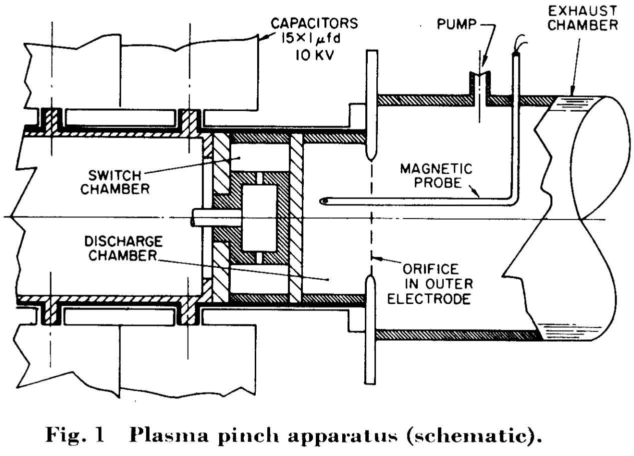

Fig. 1 Plasma pinch apparatus (schematic).

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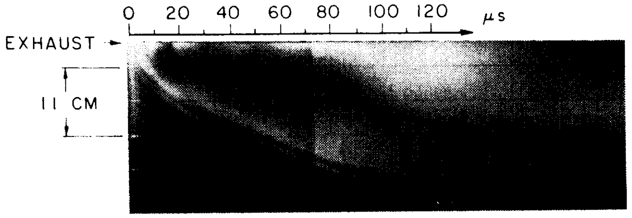


Fig. 2 Streak photograph of exhaust from 5-in. pinch. Discharge in 120-μ argon.

To check whether this effect could be ascribed to the orifice profile, simple conical nozzles with throat to exit diameters of $\frac{3}{8}:1\frac{1}{2}$-in. and $\frac{3}{4}:1\frac{1}{2}$-in. were tried and found to yield trajectories indistinguishable from those of the straight orifices of the same diameter as their throats. The tentative conclusion was that the ejection process was primarily limited by the minimum diameter of the orifice, rather than by the details of its contour. This conclusion was later supported by full field photographs of the large orifice exhaust patterns, described below.

Returning to the straight orifices, the streak photographs for the larger diameter holes reveal substantially higher initial speeds, as shown in Fig. 3, but the details of the persistence of the plume are somewhat ambiguous in this method of visualization because of strong radial effects that develop. These are better studied with full-field Kerr-cell photographs taken at selected times during the exhaust process. Since the 4-in. aperture displays these effects on the largest scale and permits maximum visibility of the interior of the discharge chamber, the bulk of the detailed study of the large-orifice exhaust process is performed on this configuration.

4. Discharge from a Large Orifice, Luminous Patterns

In the orifice-discharge chamber configuration used for this portion of the study (Figs. 1 and 4) the outer electrode exposes only about a $\frac{1}{2}$-in. annular ring to the interior of the chamber. From previous experience, this is known to be a minimum electrode dimension for the establishment of uniform cylindrical discharge sheets.[9] The pyrex exhaust vessel is now 9-in. in diameter, permitting greater lateral development of the exhaust pattern before encountering the vessel wall.

Figure 5 shows a sequence of Kerr-cell photographs looking radially into the exhaust vessel at the development of a dis-

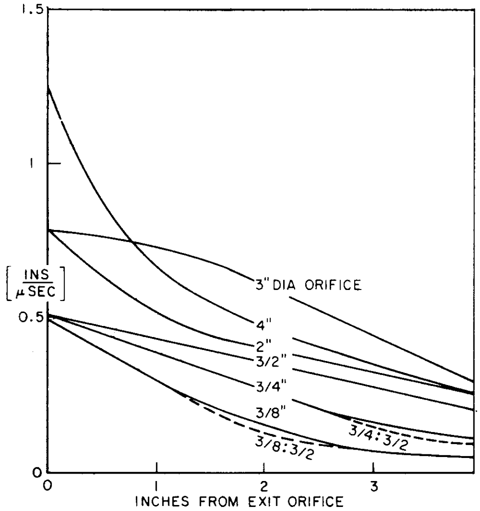


Fig. 3 Velocity of exhausted gas from orifices of different diameter in 120-μ argon.

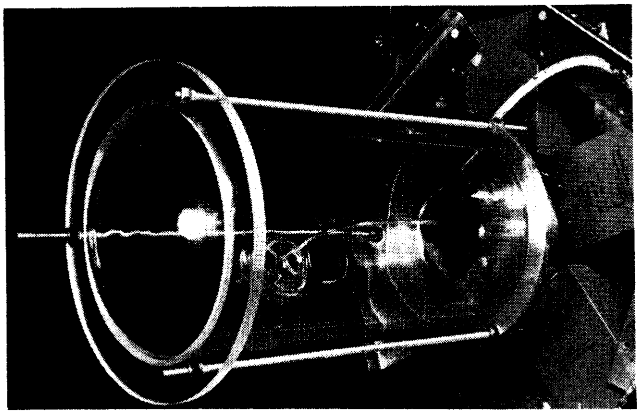


Fig. 4 Pinch discharge apparatus with exhaust chamber.

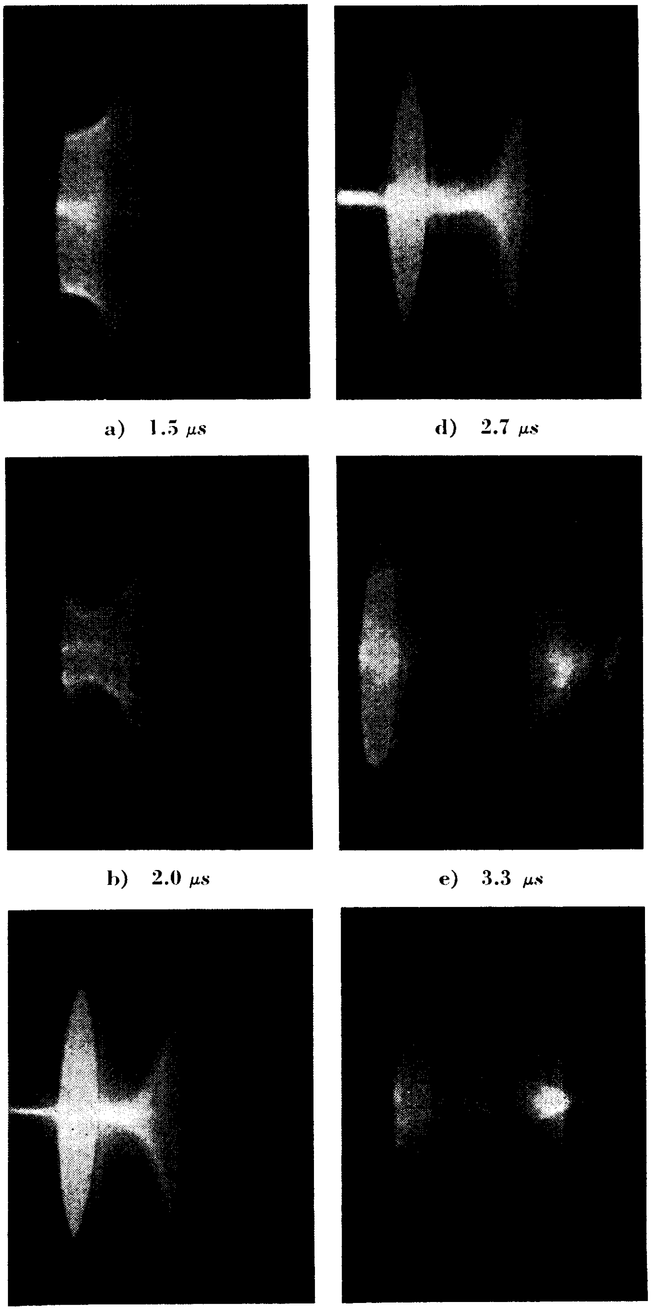
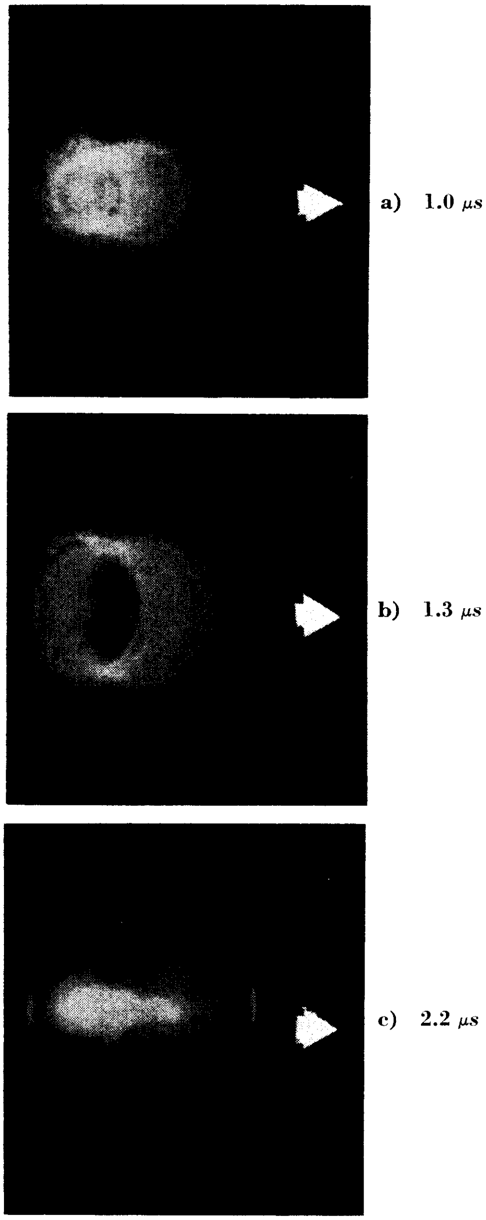

a) 1.5 μs
d) 2.7 μs
b) 2.0 μs
e) 3.3 μs
c) 2.3 μs
f) 4.5 μs

Fig. 5 Kerr-cell photographs of exhaust from constant current pinch in 120-μ argon.


a) 1.0 μs

b) 1.3 μs

c) 2.2 μs

Fig. 6 Diagonal view of pinch discharge: 120-μ argon, 4-in.-diam orifice.

charge in 120 μ argon. Figure 6 displays a similar sequence, looking diagonally into the large orifice, showing additional details of the development of the interior portion of the discharge. Three aspects of the exhaust process are clearly evident in these photographs. First, the main luminous front originally associated with the interior discharge sheet is observed to diffract outward around the edge of the orifice and then to propagate axially and radially outward into the exhaust vessel and along the outer face of the electrode. Secondly, the portion of the cylindrical luminous front inside of the discharge chamber proceeds radially inward essentially undisturbed by the presence of the large aperture in the electrode. It retains an axial and azimuthal symmetry, and a propagation speed that is indistinguishable from those found for discharges in completely closed chambers.[1] This remarkable indifference of the pinch process to the removal of a large portion of its electrode has been noted and exploited in earlier work.[10] Thirdly, when the interior pinch is completed, the central core of hot plasma thus created first streams axially outward through the orifice, and only later develops some radial growth, presumably after the pinching magnetic field relaxes somewhat. The axial thrust of this luminous column eventually pierces through the envelope of the diffracted front mentioned in Sec. 1, and sometime thereafter the entire pattern diffuses into invisibility.

Patterns similar to these are observed for discharges at the other ambient pressures ranging from 30 to 1920 μ of argon, but none of these display the preceding phenomena so distinctly as the 120 μ discharges. They are of interest, however, in comparing the outward axial speed of ejection of the pinch-heated plasma column with the interior radial speed of the imploding luminous front before the pinch is established. In all cases the ejection speed is found to be a significant fraction of the preceding radial pinching velocity (0.65 for 30 μ, 0.82 for 120 μ, 0.60 for 480 μ, and 0.54 for 1920 μ) which may imply that much of the random thermal energy resident in the pinch-heated plasma is recoverable as useful streaming motion contrary to some theoretical expectations.[11]

5. Current Density Distributions

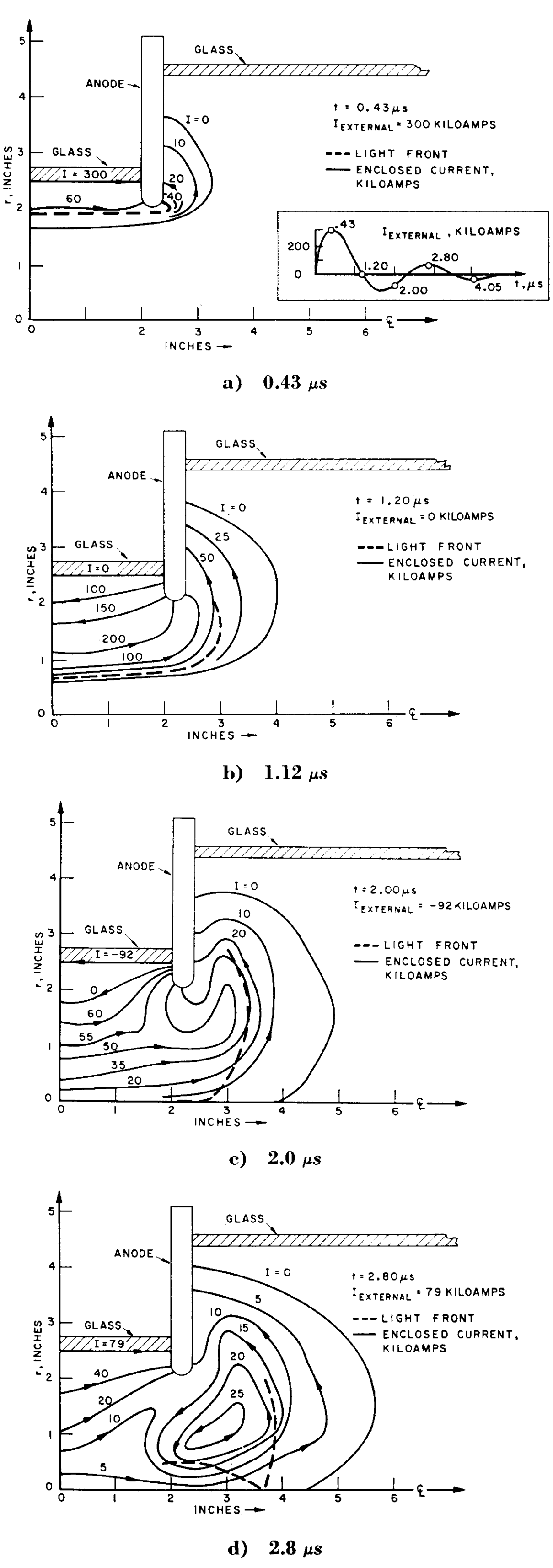
One strongly suspects that the luminous front that diffracts out of the orifice is associated with a current-carrying region, much like the luminous fronts and related current sheets inside the discharge chamber.[1] Indeed, one expects that it is the self-magnetic field trapped behind this diffracting front that is driving it outward. To confirm this concept, a series of magnetic probe surveys[12] were performed to map the development of the interior and exterior magnetic fields, and from them to deduce the current distributions inside the chamber and within the exhaust plume. The magnetic probe employed, 0.076-in. in diameter, is constructed of 3 turns of #32 formvar wire, enclosed in a 0.15-in. pyrex tube that projects axially into the discharge at the desired radial positions (Figs. 1 and 4). The signals from the probe are passively integrated on the face of a Tektronix 555 oscilloscope and displayed and photographed thereon at 0.5 μsec/cm. Typical current profiles deduced from a series of such records are shown in Fig. 7. The data here are presented in the form of total current enclosed within the radius of the field point, or equivalently, contours of the product of the local magnetic induction field and the radius. Arrowheads indicate the direction of local electron current. The location of the diffracted luminous front and the ejected pinch column at the corresponding time is superimposed as a dotted curve. It is seen that these luminous fronts are indeed associated with regions of high current density and correspondingly high magnetic body forces acting to drive them away from the orifice.

The distributions of current density and magnetic field within the chamber like the luminous front patterns are essentially the same as those found in a corresponding closed chamber experiment. No serious distortion of the profiles is found until the probe is withdrawn past the inner face of the aperture.

6. Effect of Protracted Driving Current

At later times, the current density patterns in the chamber and plume become badly distorted by the ringing of the external circuit and the "crow-bar" discharges attendant the external current reversals.[1] Although these produce certain curious effects, such as the complete detachment of a current "vortex" within the plume, and a severe recirculation pattern on the outer electrode surface, they are not the main interest of the present study. In order to remove these complications from the current distributions, the discharge apparatus was modified to accept a transmission line capacitor arrangement described in detail in another paper.[13] With this modification it was possible to apply a rectangular current pulse of 200,000 amp persisting for about 5 μsec before reversal.

Figure 8 shows the current distributions obtained in the plume and within the chamber for a 120-μ argon discharge driven by the rectangular pulse. Again the interior patterns are essentially the same as for the closed chamber discharges driven by the same circuit. The plume patterns now do not develop the vortex features found in the ringing discharge until after the end of the rectangular pulse, confirming our suspicion that these arise primarily from external circuit current reversal. Some distortion of the patterns is found near the edge of the orifice, and some near the wall of the exhaust vessel, perhaps implying a gasdynamic influence on the current trajectories there.



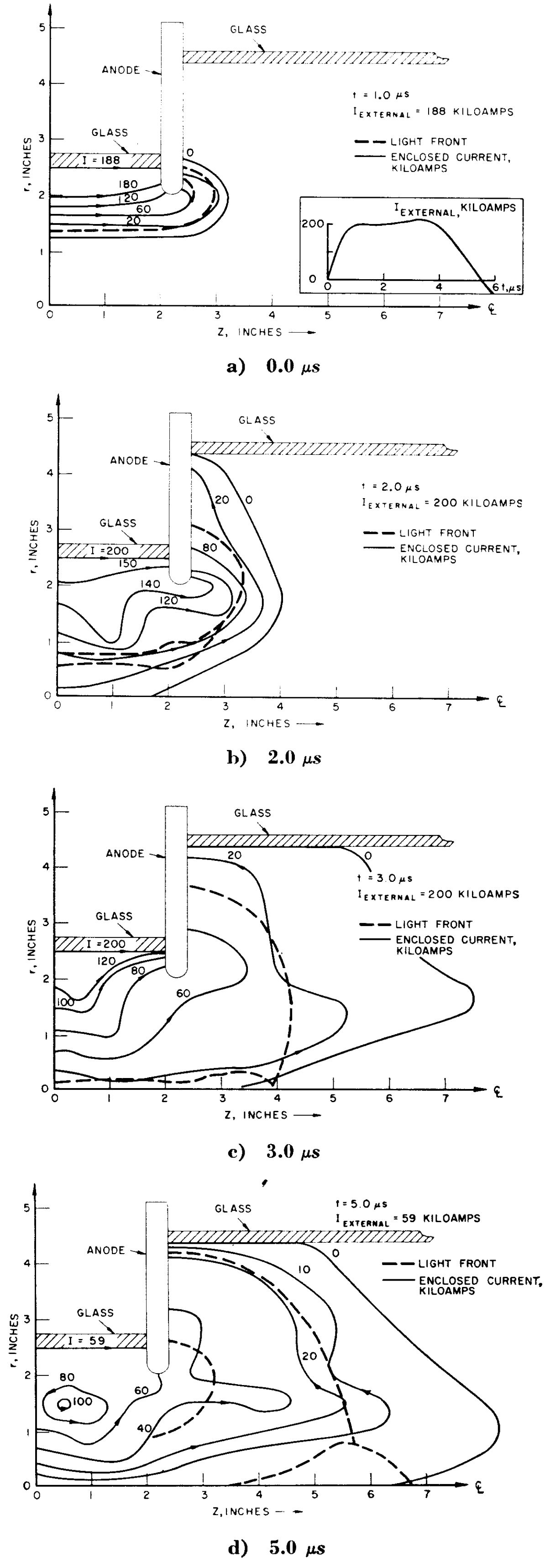
a) 0.43 μs

b) 1.12 μs

c) 2.0 μs

d) 2.8 μs

Fig. 7 Current profiles, 120-μ argon, 4-in. orifice.



a) 0.0 μs

b) 2.0 μs

c) 3.0 μs

d) 5.0 μs

Fig. 8 Current profiles, 120-μ argon, 4-in. orifice.

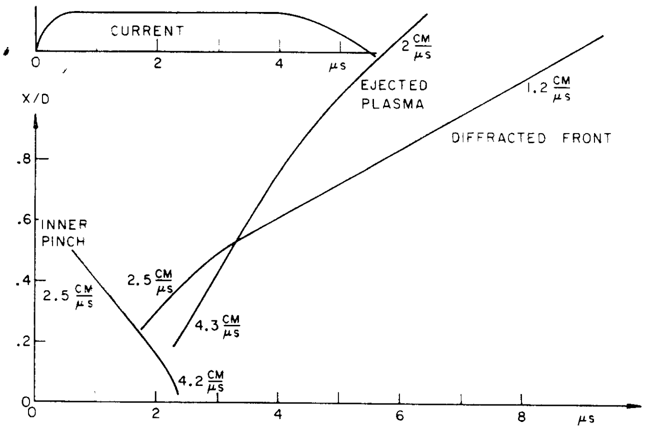


Fig. 9 Luminous front trajectories.

The luminous phenomena occurring in the rectangular pulse discharges are observed to be qualitatively identical to those seen in the ringing discharge. In fact, the photographs displayed in Fig. 5 were actually obtained with a protracted current pulse. The absolute velocities of the various fronts are somewhat higher, however, corresponding to the protraction of the magnetic driving forces. Figure 9 compares the radial trajectory of the interior front with the axial trajectories of the diffracted front and the thermal column. Note that now the axial expansion of the pinch column begins with speeds substantially higher than that of the foregoing interior radial motion, again indicative of substantial recovery of the thermal energy deposited in this column.

7. Discussion

In passing, it may be relevant to examine the progressive nature of the entire ejection process. Whereas the radial and axial outward propagation of the diffracted front seems reasonable in view of the appropriate magnetic body forces supplied by the field trapped behind it, there are several well-known situations, at least superficially comparable, where such current sheet propagation does not occur. For example, in the presently popular high impulse arcjets[14] a radial current zone of high density remains attached to the edge of the anode orifice. Similarly, experiments with pseudo-steady flow coaxial guns[11,15] show that the transient propagation of the current sheet down the barrel terminates with the current zone stabilizing at the barrel exit rather than detaching or billowing out into the exhaust tank. The criterion that distinguishes the two behaviors is at present not clear. Further experiments with longer duration driving current pulses and larger exhaust vessels may possibly reveal an eventual stabilization of the exhaust pattern.

In addition, one must concede that the ejection of the plasma into a vessel containing gas at the same ambient pressure does not necessarily simulate the process that would develop upon similar ejection into a hard vacuum. Thus the relevance of these observations to the behavior of a plasma thrustor in space may be indirect. To simulate the latter situation, however, involves major experimental changes, most notably the operation of the pinch chamber itself in a gas injection mode, an operation replete with many well-known problems of synchronization and discharge instability.[4] That is, one will then study the ejection of a substantially different type of plasma discharge from that obtained in the uniform gas environment used in the foregoing. Nevertheless, the techniques described here should be directly applicable to the study of such gas-pulsed thrustors, as well as to all other intermittent plasma accelerators.

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