TECHNICAL NOTE

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EXPERIMENTAL STUDY OF

A SINGLE-COIL INDUCED-ELECTROMOTIVE-FORCE

PLASMA ACCELERATOR

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SUMMARY

An experimental study was made of a single-coil induced-electromotive-force plasma accelerator which used a capacitor discharge for the driving force. A strong shock was observed from the first pulse with a velocity of 10^6 centimeters per second. This shock was followed by three or four discharges which produced plasmoids moving at about 5×10^6 centimeters per second. The efficiency of the accelerator was estimated to be about 3 percent in the production of the high-velocity plasmoids. Suggestions are made for the improvement of this type of accelerator.

INTRODUCTION

A comparatively simple device used to accelerate plasma and consisting of a large current pulse through a single-turn coil has been briefly discussed in the literature concerning fusion processes. This device has usually been utilized for an auxiliary purpose and, as a result, has not been considered in detail. One such incomplete study is found in reference 1, in which this single-turn accelerator was used to insert a highly conductive shock plasma into a traveling-wave accelerator. Another mention is made in reference 2, where the device was utilized to insert plasma into the Ixion, a possible thermonuclear machine. This device is also basic to Scylla, another nuclear fusion machine, discussed in reference 3. In view of the fact that this plasma accelerator has several interesting features, such as that no electrodes are in contact with the plasma and that no metallic wires or high-temperature metallic vapors are required in its operation, it was believed that a more thorough study of the system might show interesting features not previously discussed.

A simple experiment to demonstrate the properties of this type of accelerator involves locating a pancake or flat-wound coil in juxtaposition to a gas at or near minimal arc breakdown pressure. This coil may then be energized with a rapidly varying current pulse which will induce an electromotive force in the gas capable of forming a plasmoid and accelerating it to a high velocity.

This paper presents the results of various experiments made with this type of plasma accelerator. These results are intended to show the feasibility of the use of this accelerator and to indicate future lines of development which should improve its performance as a means for obtaining very high gas velocities at low densities.

SYMBOLS

C capacity of drive condenser (from name plate), μf

E_2 kinetic energy, $m^2 V_2^2/2$, j

E_{2t} total energy loss on second half-cycle, $W/2f$, j

f oscillation frequency (measured), cps

I_1 peak current on first half-cycle, $EC\omega$, amp

I_2 peak current on second half-cycle, $I_1 \frac{I_2}{I_1}$, amp

L_c inductance of circuit with drive coil shorted, $1/\omega_c^2 C$, μh

L_d inductance of drive coil, $L_t - L_c$, μh

L_t total inductance of circuit, $1/\omega^2 C$, μh

m_2 estimated mass accelerated on second half-cycle (10-percent ionization assumed), kg

$Q = \frac{\omega L_d}{R}$

R resistance of circuit (calculated), ohms

r accelerator-cup radius (measured), cm

V capacitor charging voltage (measured), v

V_2 velocity of gas attained on second peak (measured), m/sec

W_2 energy loss rate on second half-cycle, $I_2^2R/2$, w

ω angular frequency, $2\pi f$, radians/sec

ω_c angular frequency with drive coil shorted (measured), radians/sec

PRINCIPLE OF INDUCED-ELECTROMOTIVE-FORCE PLASMA ACCELERATOR

The induced emf (electromotive force) plasma accelerator is essentially an air-core transformer in which the primary circuit is a fixed coil and the secondary circuit is an arc flowing in a closed path in the gas next to the primary coil. If the arc is permitted to form in a region of the magnetic field which contains a radial component, a force exists between the magnetic fields of the arc current and the drive coil which will accelerate the plasmoid. This acceleration can be of the order of 10^{12} meters per second per second if the mass of the plasmoid is small (10^{-9} to 10^{-10} kilogram) and the magnetic forces are large (several hundred newtons). Such forces are quite realizable with currents of the order of 10,000 to 100,000 amperes. Accelerations of this order can give velocities of about 10^4 to 10^5 meters per second in distances of the order of 1 or 2 centimeters.

EXPERIMENTAL EQUIPMENT

The basic accelerator circuit, a modification of the circuits presented in references 1 and 4, is shown in figure 1. The portion of figure 1 involved in the basic circuit consists of the 16,000-volt charging source, the capacitor C_1, the spark-gap switch Sw_2, and the primary coil. The capacitor C_1 consisted of two parallel connected, 0.55-microfarad, low-inductance capacitors. The various primary coil configurations used to accelerate the plasma are shown in figure 2.

The low-pressure chamber in which the plasma was formed is shown in figure 3 and consisted of a glass tube 6 inches in diameter by 12 inches long, used as a runway for the plasma. One end of the tube was covered with plate glass through which visual observation could be made; the other end was covered with a bakelite plate having a 2-inch-diameter hole through the center into which a Lucite cup (fig. 4) was inserted. The primary or drive coil was mounted on the exterior of the cup with the interior of the cup free for the formation of the plasmoid. The pressure in this space was held at values of 1 to 600 microns of mercury by suitable vacuum pumps.

Several auxiliary circuits were used for the control of the main discharge. The main discharge was controlled by a spark-gap switch. (See fig. 1.) This switch was made up of two parallel plates set sufficiently far apart to avoid arcing when the main capacitor was charged to the voltage required for the test. An auxiliary electrode in the gap was connected to a spark coil circuit which was manually controlled. The firing of this circuit broke down the gap and permitted the main capacitor to discharge through the primary coil.

Another auxiliary arc (fig. 4) was used to preionize the gas. This preionization was beneficial, as it greatly reduced the voltage gradient required to form the induced arc in the gas and allowed the magnetic field a greater time to act upon the ionized gas. The preionization was accomplished by discharging a 0.01-microfarad capacitor through the gas in the cup. The main drive capacitor was discharged immediately afterwards and thus a high degree of ionization in the gas was assured. The circuit which controlled this operation is shown in figure 1.

In the operation of this circuit the capacitors C_1 and C_2 were initially charged to the full voltage of the charging circuit and capacitor C_3 was at ground potential. The spark-gap switches Sw_1 and Sw_2 operated as described previously in this section. The discharge was initiated by firing the control spark of switch Sw_1; this caused capacitor C_2 to discharge through switch Sw_1 and the preionization gap into capacitor C_3. The resultant increase of the potential in capacitor C_3 caused a spark to form in the control gap of switch Sw_2 which allowed the main capacitor to discharge through the drive circuit. Thus, the main capacitor discharged at the time when the preionization arc was flowing through the gas within the accelerator cup. The 3-megohm resistor prevented the main capacitor from discharging through switch Sw_1. The 1.5-megohm resistor assured that capacitor C_3 would be initially at ground potential.

MEASUREMENTS

Other instrumentation was required to determine the nature of the plasma which occurred when the capacitor was discharged through the drive coil. First, the current in the discharge could be estimated from a knowledge of the circuit constants, oscillation frequency, and damping coefficient. The oscillation frequency and damping coefficient were determined from the emf induced in a small coil located in the neighborhood of the primary coil. The output emf induced in this coil was measured with an oscilloscope. The tracings were photographed with a camera attached directly to the oscilloscope.

Time-integrated exposures were also made of the discharges to give a permanent record. These photographs gave qualitative information on the spatial extent and intensity variation of the flash.

The actual velocity measurements were made by exposing a slit view of the discharge to a rotating-mirror camera. The slit was made by covering the glass tank with cardboard except for a small narrow opening. An optical train (fig. 5) was set up which swept an image of the slit along a sheet of camera film. Thus, a trace was created on the film from which the velocity could be determined.

The tank pressure prior to the discharge was obtained with a thermopile-type vacuum gage capable of measuring pressures from 0.001 to 1 millimeter of mercury.

PRESENTATION OF RESULTS

Several time-integrated photographs of the plasma pulses are shown in figures 6, 7, and 8. Figure 6 shows side views of several plasma pulses from discharges made with the cup coil in which the initial pressure in the chamber varied from 600 to 50 microns of mercury. The preionization arc system was used for these discharges. Similar side views of plasma pulses, in which the discharge was made with no preionization in the cup, are presented in figure 7. Two end views of different plasma pulses are shown in figure 8.

Photographs were taken with a rotating-mirror camera of plasmoids accelerated by each of the three coils shown in figure 2. Two typical photographs of this series are presented as figure 9. The gas pressures for these tests were held to about 70 microns of mercury. A series of discharges made with the cup coil was also photographed to show the effect of pressure variation; for this series the initial pressure was varied from 50 to 120 microns of mercury. The plasmoids could not be photographed at pressures below 50 microns of mercury because of insufficient light to expose the film; also, preionization was required to obtain successful film exposure. The axial velocity of each of the various plasmoids was determined from the slope of the leading edge of its streak on the film along with a calibration factor determined from the rotational frequency of the mirror (about 1,700 revolutions per second) and the dimensions of the system. The measured velocities are presented in figures 10 and 11.

DISCUSSION OF RESULTS

Nature of Plasma Pulse

Figures 6 and 7 show that a restricted core of plasma extends from the cup for a range of 5 to 10 centimeters. Since such a core either could be formed instantaneously by the induced field or could be formed by a plasmoid moving through this space, it is necessary to refer to the photographs of figure 9. This figure shows that the core was not formed instantaneously but rather was formed by a moving plasmoid.

The phenomena shown in this photograph can be more fully understood if attention is called to the fact that the Q of the electrical circuit is high enough to cause electrical oscillations for several cycles after the capacitor discharge was initiated. Although this electrical oscillation damped out rapidly, there was sufficient energy to reinduce plasma rings for the first four or five cycles. If the coil had been placed around the center of a long cylinder, plasma rings would have been observed moving away from the core of the primary coil in both directions on each half-cycle. In this experiment, however, the cup would permit the ejection of plasma rings in only one direction. Figure 9 shows the effect damping had on these plasma rings. The induced current in the plasma ring is 180° out of phase with that of the primary coil; thus, the magnetic field set up by the currents of the primary coil and the plasma ring result in a force which accelerates the plasma ring away from the primary coil. The expansion or contraction of the plasma ring as it moves away from the primary coil is governed by several components. The axial field of the primary coil applies a force component tending to reduce the diameter of the plasma ring; whereas, the magnetic field of the plasma ring produces an outward component, as does the joule heating. The vector sum of these forces together with the inertial forces determines the behavior of the plasmoid. The data of this experiment indicated no expansion of the plasma ring when moving outward.

Two end views taken at different pressures are shown in figure 8. Both views show a definite ring formation. The sharp outer ring boundary is due to the wall of the cup. The dark central region seen in both views indicates either some pulling together of the plasma or, more likely, failure of breakdown associated with the small voltage gradient in that region.

Effect of Pressure Variation

Figures 6 and 7 show the effects of varying the initial pressure in the tank. Varying the pressure causes a change in the density of gas in the plasma and, hence, in the mass to be accelerated. The breakdown potential required to form the plasma is also changed. Increasing the pressure increases the resistance to the motion, as the ring must push through a denser gas. Thus, the plasma is propelled only a short distance at high pressures. At a pressure of 600 microns of mercury the plasma ring does not get out of the cup; whereas, if the pressure is lowered, both the range and amount of plasma increases, this increase indicating a more efficient action of the acceleration system. A maximum range and amount of plasma are seen to occur at about 75 microns of mercury. If the gas pressure is much less than 75 microns of mercury, the density of the gas becomes too low for the plasma to form readily. In fact, at pressures below 50 microns of mercury the plasma could not be formed by the preionization arc circuit of figure 1. Thus, this series of discharges was not extended to pressures below 50 microns of mercury.

It was found that, even though the electrostatic, or preionization, arc would not form at a pressure below 50 microns of mercury, an arc could be formed by electro-magnetic induction. Figure 7 shows plasma formed at pressures below the pressure at which electrostatic breakdown occurs and indicates that reducing the density of the plasma reduces the light intensity.

The fact that an arc can be formed by the induced emf whereas none can be formed by the electrostatic voltage gradient is a direct result of Paschen's law. (See ref. 5.) In the case of the induced emf, the length of the path available for arc formation is very long, since the charged particles travel around a circular path many times and thereby create a sufficient number of ions so that an arc can form. In the case of the electrostatic arc, however, the length of the path of the charged particles is so short that a charged particle does not form enough ions during its traverse of the path to cause an arc and, hence, no breakdown can occur.

Time History of Pulse

The leading streak (fig. 9), which starts with the initial discharge and indicates the boundary between the quiet gas and the gas affected by the plasma, is quite sharp. This streak is caused by the strong shock front which separates the quiet gas from the rapidly moving gas caused by the acceleration discharge. This shock, briefly mentioned in references 1, 2, and 3, contains the hot gas and plasma.

The initial discharge is followed by several smaller decaying discharges, all of which result from the oscillatory nature of the electrical circuit. The plasmoids formed by these less intense discharges produce shock fronts which have velocities substantially above the velocity of the leading shock. These shock fronts appear to overtake the leading shock and support it with additional energy.

Velocities of Plasmoids

Figure 10 presents the velocities of the various pulses which were derived from streak photographs similar to the one shown in figure 9. The velocities of various pulses for several tank pressures are shown in figure 11. In this figure all velocities having the same symbol are comparable, inasmuch as these velocities were produced with the same coil.

Figure 10 shows that after the initial shock front was set up the velocity of the plasmoids following the second half-cycle tended to be reduced as the maximum current was reduced. Such a result is to be expected because a lower maximum current not only reduces the forces involved but also reduces the induced voltage gradient that creates the plasmoid. Although the reduction of velocity appears to be linear, the inaccuracies involved in measuring the slopes of the streaks are sufficiently great to disallow such a claim. Thus, only a reduction of velocity with reduced drive current can be reasonably claimed.

The effect of varying coil shape is also seen in figure 10. The three-turn coil accelerator (fig. 10(b)) produced lower velocities than either of the single-turn coils (fig. 10(a)), even though the initial energy stored in the capacitor was the same. The cup-coil accelerator and the flat-coil accelerator produced practically the same velocities; this indicated that these somewhat different shapes had very little effect on the velocity.

As shown in figure 11, the plasma velocities are affected by varying the initial pressure. As might be expected, the denser the neutral gas is, the smaller the plasma velocity. With increased density the transformer relationship and, therefore, the current in the plasma ring remain relatively unchanged. The forces which accelerate the plasma are, therefore, more or less unaffected and the acceleration of the denser plasma is reduced.

ANALYSIS OF CIRCUIT PARAMETERS

An estimation of the operational characteristics and energy conversion efficiency requires determination of the various circuit parameters. These parameters were determined from the oscillographs of the damped frequency discharge of the capacitor and coil circuit. The mass of the second of the series of plasmoids produced by the oscillatory discharge was used to estimate the thrust and energy output. This mass was not measured but was estimated by assuming that 10 percent of the mass of the gas in the cup was ionized. This percentage value might be as great as 20 percent or even as low as 1 percent. The results of the measurements, calculations, and estimations are presented in table I.

Operational Characteristics

An estimation of the voltage gradient required to form the plasma ring can be obtained by multiplying the voltage applied to the drive coil by an estimated coupling coefficient and dividing by the radius of the ring. The voltage across the drive coil is determined by multiplying the charging voltage V by the ratio of the inductance of the drive coil to the total inductance of the circuit L_d/L_t. The drive-coil voltage is, therefore, seen to be about 6,400 volts. Using an assumed coupling coefficient of 0.75 results in 4,800 volts being applied to the gas ring. The voltage gradient about the plasma ring with an assumed radius of 2 centimeters is then 380 volts per centimeter. This voltage gradient is believed to have been large enough to produce a conductivity in the plasma ring so great that the inductive reactance controlled the current. If such is correct, the maximum current in the plasma ring should equal the drive current multiplied by the coupling coefficient, or about 10,000 to 30,000 amperes.

The fact that only 6,400 volts of the 16,000 charging volts was applied to the drive coil indicates an inefficient application of the charging voltage to the drive circuit. Any increase in the ratio L_d/L_t either increases the voltage gradient about the plasma ring or reduces the charging voltage required to operate the system. Such an increase of L_d/L_t is possible if use is made of an integrated design of the capacitor and drive coil in which the lengths, spacing, and inductance of all current paths are kept to an absolute minimum.

The use of such a coil and capacitor unit should also help to reduce the resistance (0.046 ohm) found in this circuit. This total circuit-resistance value is high compared with the approximate value of 0.0004 ohm, the resistance of the drive coil as computed by use of the standard formulas for skin depth penetration and resistivity. The spark-gap switch contributes to the high inductance and resistance values. The elimination of this switch, as can be done in a continuously operating system, should be a definite improvement in reducing the circuit inductance and resistance.

Efficiency of Energy Conversion

In table I the efficiency of this accelerator is shown to be 3 percent. It is believed possible to effect substantial improvements in the efficiency of the accelerator by using the ideas suggested in the section entitled "Operational Characteristics." For example, if the total resistance were reduced from the measured value of 0.046 ohm to a value of ten times the estimated coil resistance, or 0.004 ohm, the estimated energy conversion efficiency should be increased to about 35 percent. The use of an accelerator operating at this efficiency could be considered to be reasonable for application to such devices as high-speed wind tunnels or experimental fusion machines where the equipment required to remove the heat loss does not add a severe penalty to the use of the system. Further improvement of the velocity might be obtained from operation into a higher vacuum than was used for these experiments; also, improvements might be expected from choice of optimum coil dimension, drive currents and frequencies, and initial voltage gradients.

Continuous Operation

The series of accelerations occurring during a discharge of the capacitor could be considered as a pseudocontinuous type of operation. This phenomenon is an indication that the accelerator could operate continuously if the gas were fed into the cup properly and the maximum value and frequency of the drive current were held at the corresponding maximum values of the experimental drive current. In such a continuous operation the mass flow should be easily controlled. Only simple valves would be required in contrast to the equipment needed to feed molten or vaporized alkali metals or solid pieces of wire into an accelerator chamber. It is also possible to use low-atomic-number gases from which high specific impulses can be obtained.

Low-Power Continuous Operation

A simple analysis of a single-coil system, similar to the accelerator studied in this report, in which the plasma was assumed to be a highly conducting ring of constant radius and free to move coaxially away from the drive coil, indicated that drive-coil currents of the order of 10 to 20 amperes should drive very light rings (10^{-14} kilogram) to velocities on the order of 10^4 to 10^5 meters per second. A continuous-operating accelerator which met the above conditions was set up to check the analysis. The experiment used an 80-micron-liter-per-second oil-diffusion pump to maintain gas flow and a 4-megacycle-per-second, 2-kilowatt, radio-frequency oscillator as a power source, which gave about 20- to 40-ampere turns in the drive circuit. In all the tests made, no acceleration of the generated plasma was detected. Since no acceleration was detected, the actual forces existing between the plasma and the drive coil were much smaller than computed. This difference is believed to be due to the fact that the limited number of electrons of the plasma ring can not be accelerated to an azimuthal velocity sufficiently great to permit the electrons to carry the necessary current required in the analysis. It is possible that a maximum velocity of the plasma ring exists for a given drive current and that this velocity can not be increased by reducing the number of particles in the ring. This condition may eliminate the use of the induced emf plasma accelerator in cases involving very small mass flows and low power levels.

CONCLUDING REMARKS

The results of these experiments on induced-electromotive-force plasma accelerators showed several interesting phenomena.

The accelerator produced a shock-wave pulse with a velocity of the order of 10^6 centimeters per second. This pulse was followed by a series of three or four pulses moving at higher velocities - that is, about 5×10^6 centimeters per second.

The efficiency of the system for the high-velocity series of pulses obtained in the present investigation was estimated to be about 3 percent. Obvious modification, such as elimination of the spark-gap switch and better design of the coil and capacitor, should improve this factor.

The axial velocities of the plasmoids followed certain expected trends; that is, the velocities were reduced with either reduction of the drive current or increase of the initial gas pressure.

Induced-electromotive-force discharges were found to occur at pressures well below the pressure at which electrostatic breakdown failed to occur.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Field, Va., October 3, 1960.

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TABLE I.- CIRCUIT PARAMETERS

Accelerator-cup radius, r, cm	2.5
Accelerator-cup depth, d, cm	2.0
Capacity of drive capacitor, C, μf	1.1
Oscillation frequency, f, cps	369,000
Angular frequency, ω, radians/sec	2,316,000
Angular frequency with drive coil shorted, ω_c, radians/sec	2,980,000
Inductance of drive coil, L_d, μh	0.068
Inductance of circuit with drive coil shorted, L_c, μh	0.101
Total inductance of circuit, L_t, μh	0.169
Capacitor charging voltage, V, v	16,000
Energy stored, $CV^2/2$, j	141
Peak current on first half-cycle, I_1, amp	40,750
Peak current on second half-cycle, I_2, amp	34,000
Peak current ratio, I_1/I_2	1.2
Resistance of circuit, R, ohm	0.046
Energy loss rate on second half-cycle, W_2, w	26.5×10^6
Total energy loss on second half-cycle, $E_{2,t}$, j	36.1
Initial mass of gas in cup at 100-micron pressure, m_1, kg . .	7×10^{-9}
Estimated mass accelerated on second half-cycle (assuming 10-percent ionization), m_2, kg	7×10^{-10}
Velocity of gas attained on second peak, V_2, m/sec	6×10^4
Kinetic energy, E_2, j	1.26
Electrical energy converted to gas energy (based on values herein), $\frac{100E_2}{E_{2,t}}$, percent	3
Impulse of second plasmoid, m_2V_2, $\frac{\text{kg - m}}{\text{sec}}$	4.2×10^{-5}
Thrust assuming continuous operation, $2m_2V_2f$, newtons . .	31 (or 7.4 lb)
Power required for gas acceleration, $m_2V_2^2f$, kw	900
Specific impulse, V_2/g, sec	6,000

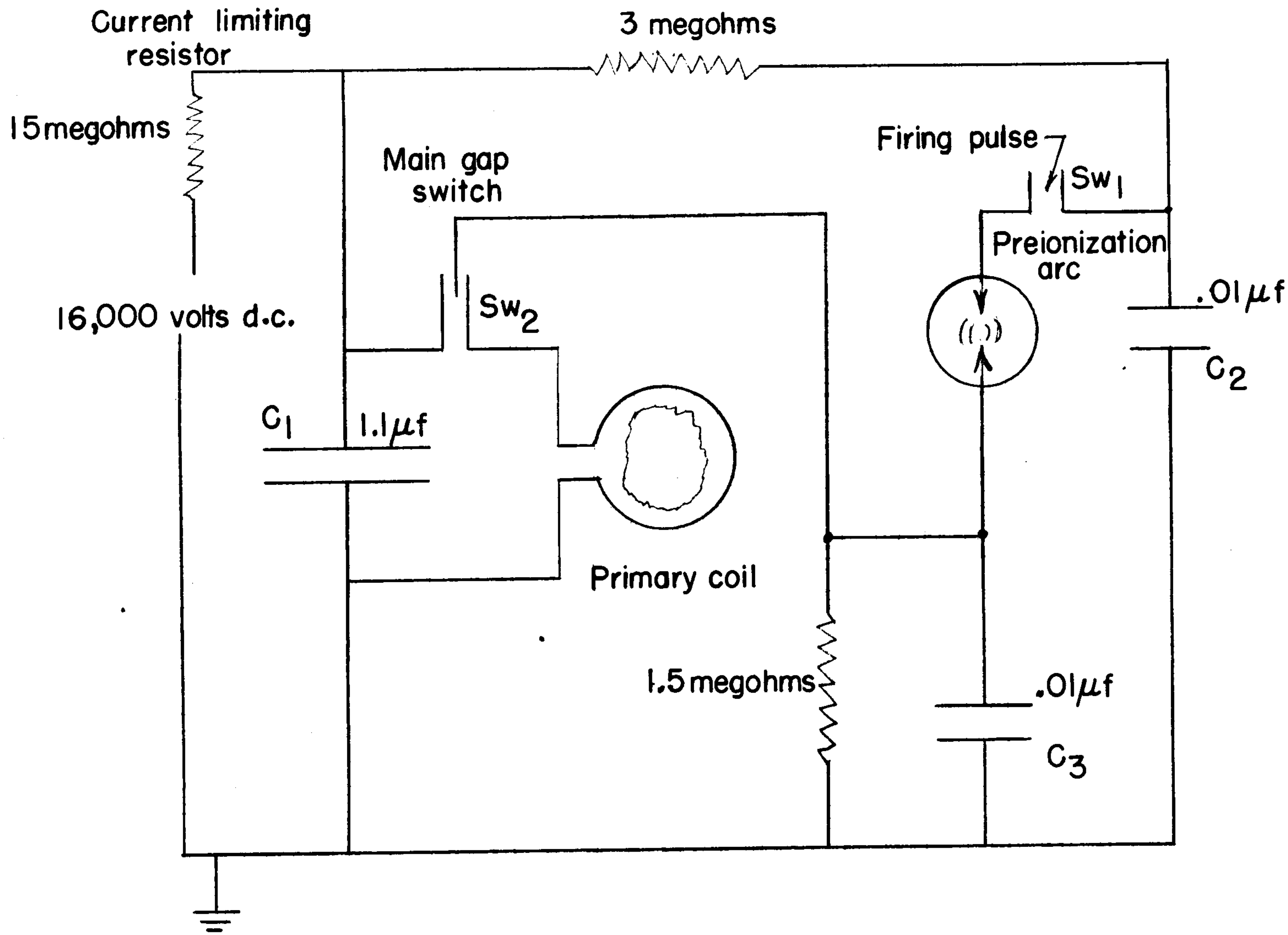


Figure 1.- Main drive circuit with a preionization arc circuit.

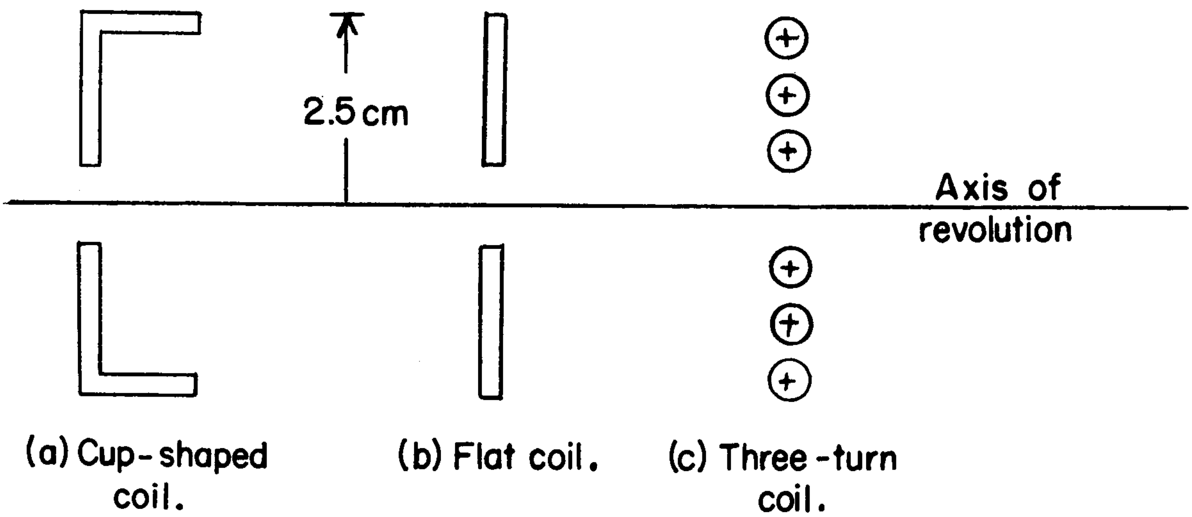


Figure 2.- Diagram of various drive coils tested.

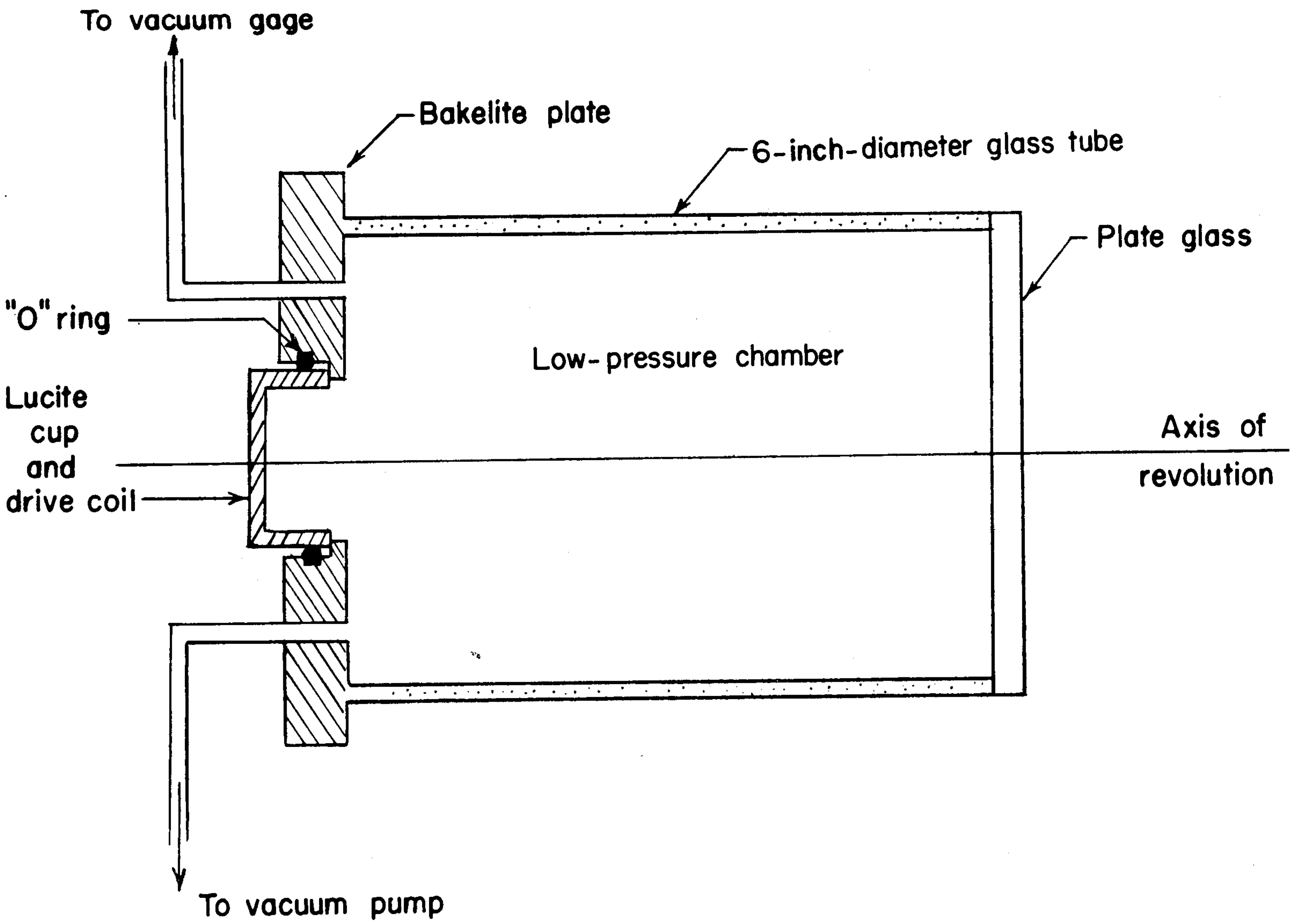


Figure 3.- Schematic diagram of vacuum accelerator chamber.

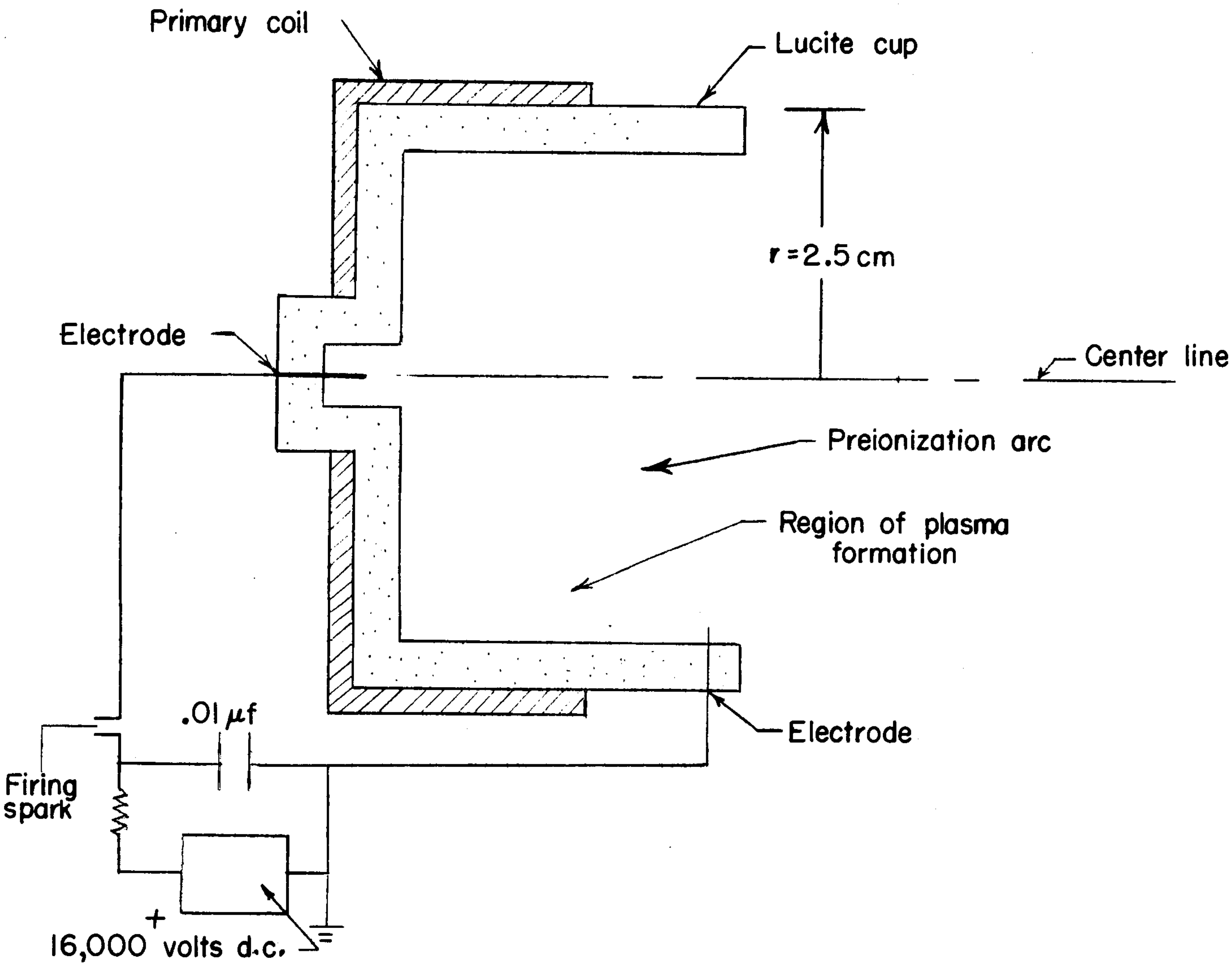
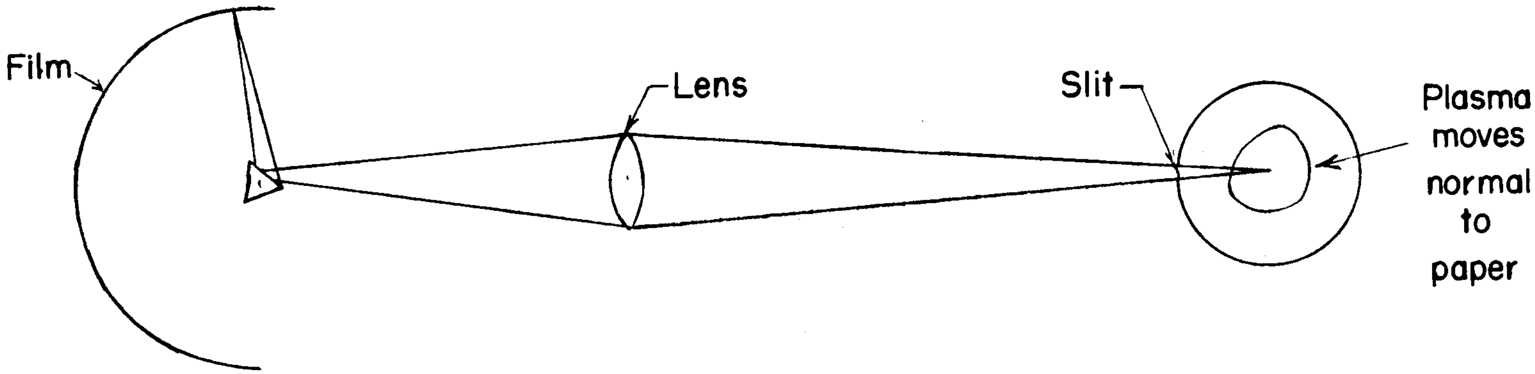
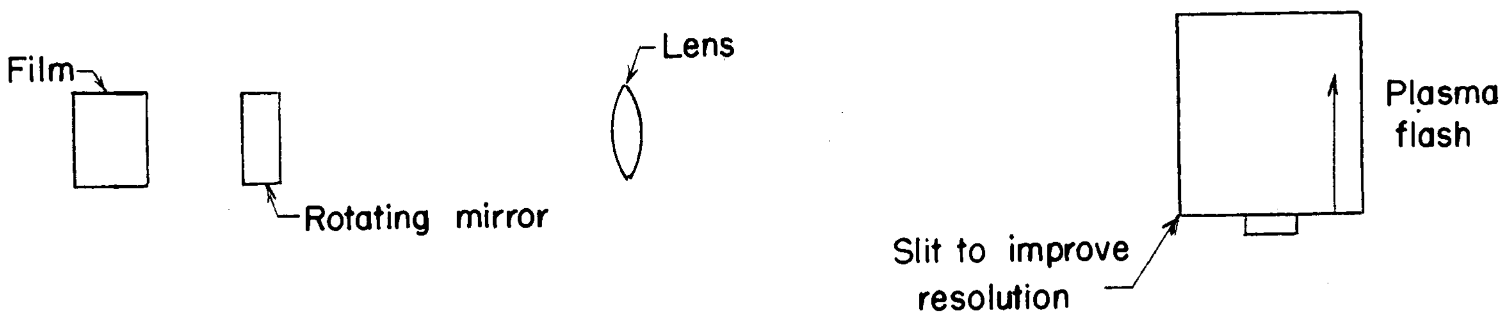


Figure 4.- Accelerator cup and preionization arc circuit.

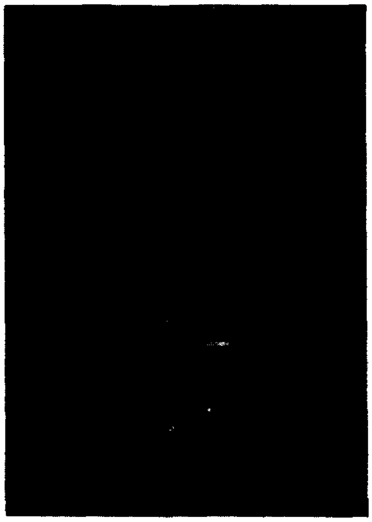


(a) Top view.

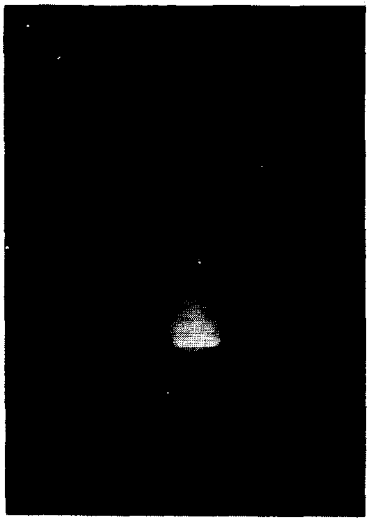


(b) Side view.

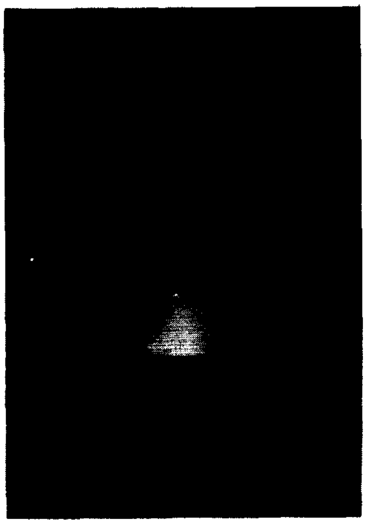
Figure 5.- Optical system for measuring velocity of plasma flash.



(a) Tank pressure, 600 μ Hg.

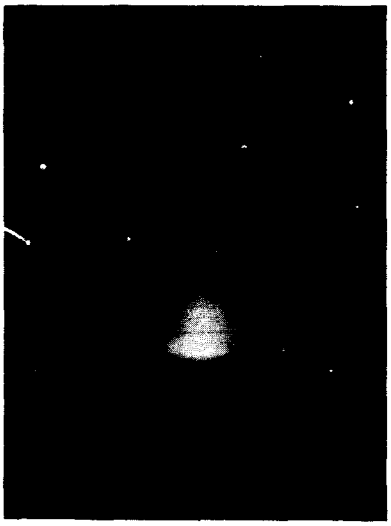


(b) Tank pressure, 300 μ Hg.

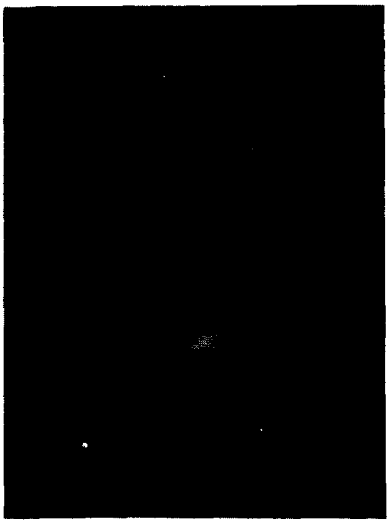


(c) Tank pressure, 100 μ Hg.

Scale 2 inches



(d) Tank pressure, 75 μ Hg.



(e) Tank pressure, 50 μ Hg.

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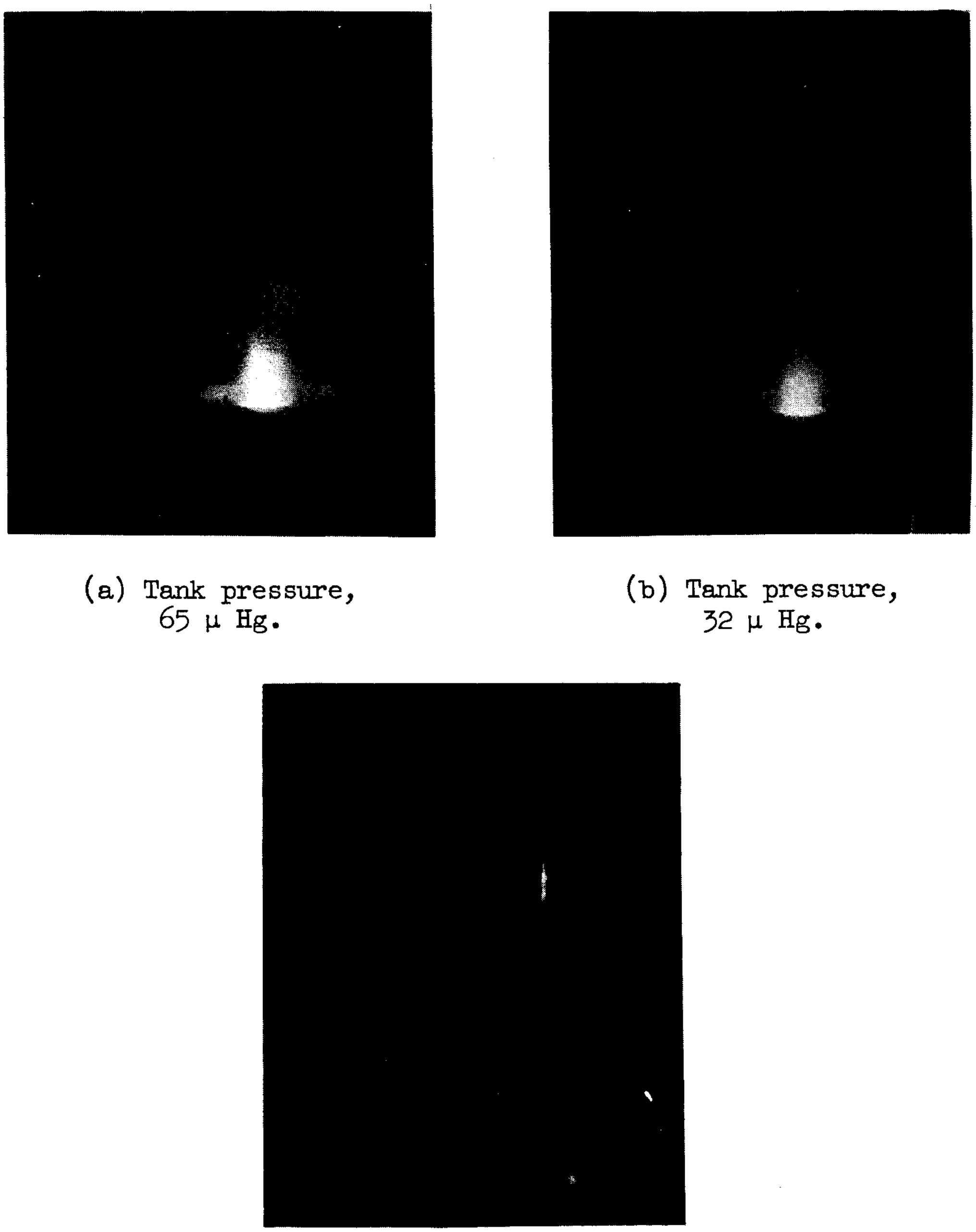
Figure 6.- Side view of several plasma pulses from discharges with preionization, showing effects of pressure variation. Cup coil.



(a) Tank pressure, 65 μ Hg.

(b) Tank pressure, 32 μ Hg.

(c) Tank pressure, 1 μ Hg.

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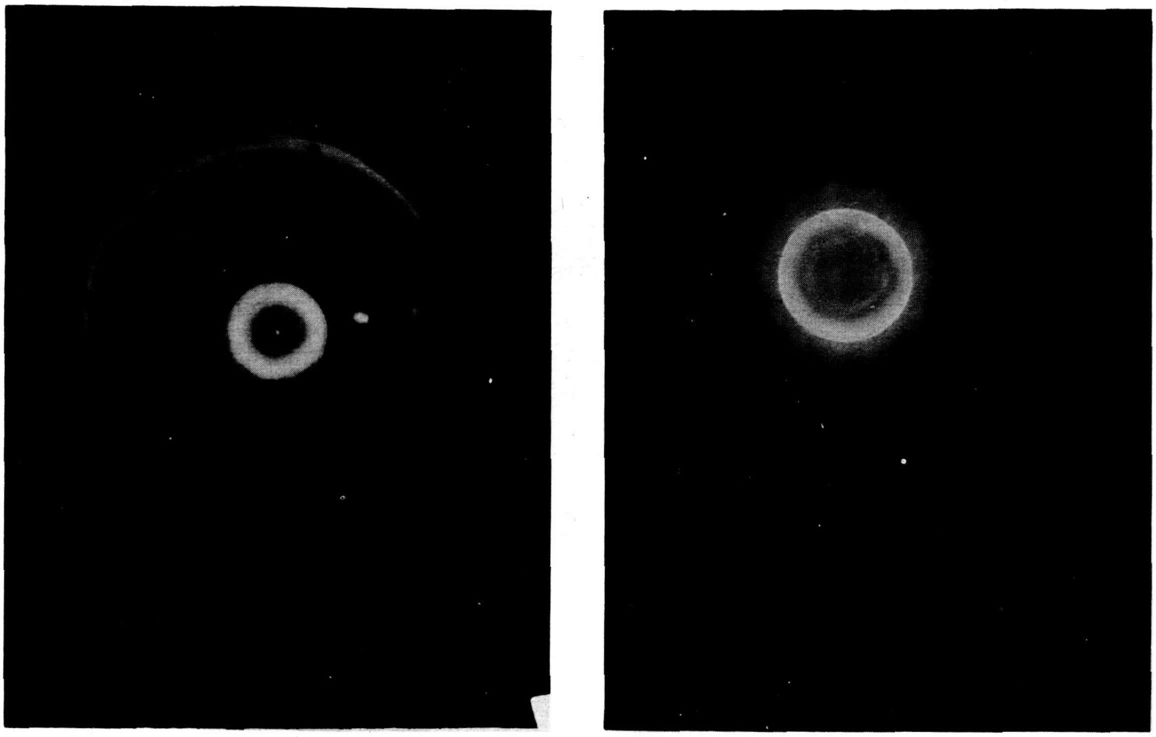
Figure 7.- Side view of several plasma pulses from discharges without preionization. Cup coil.



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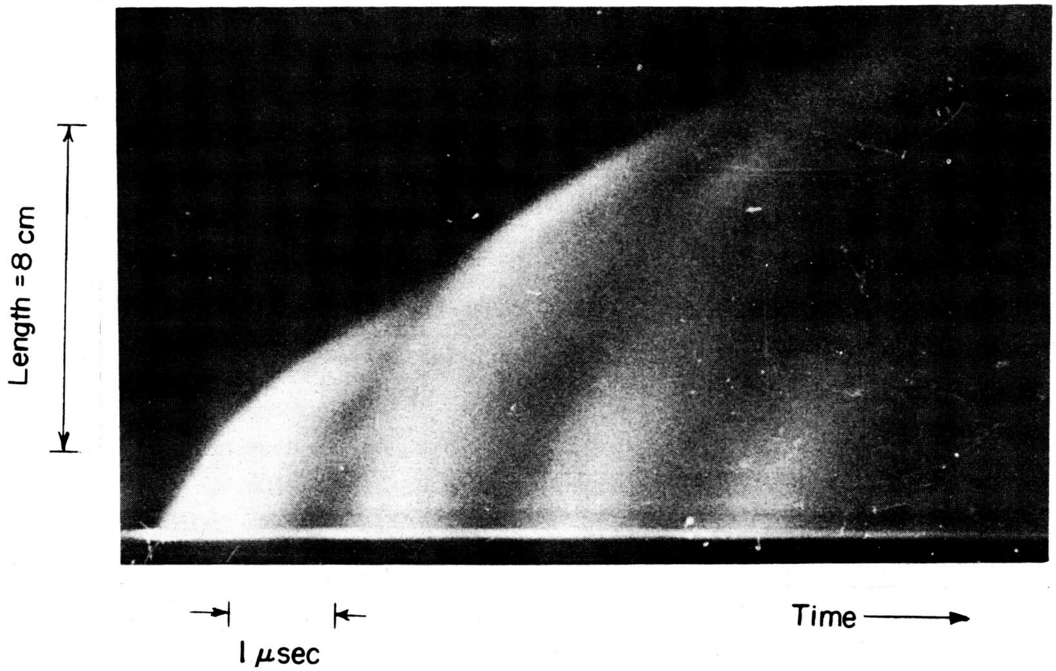
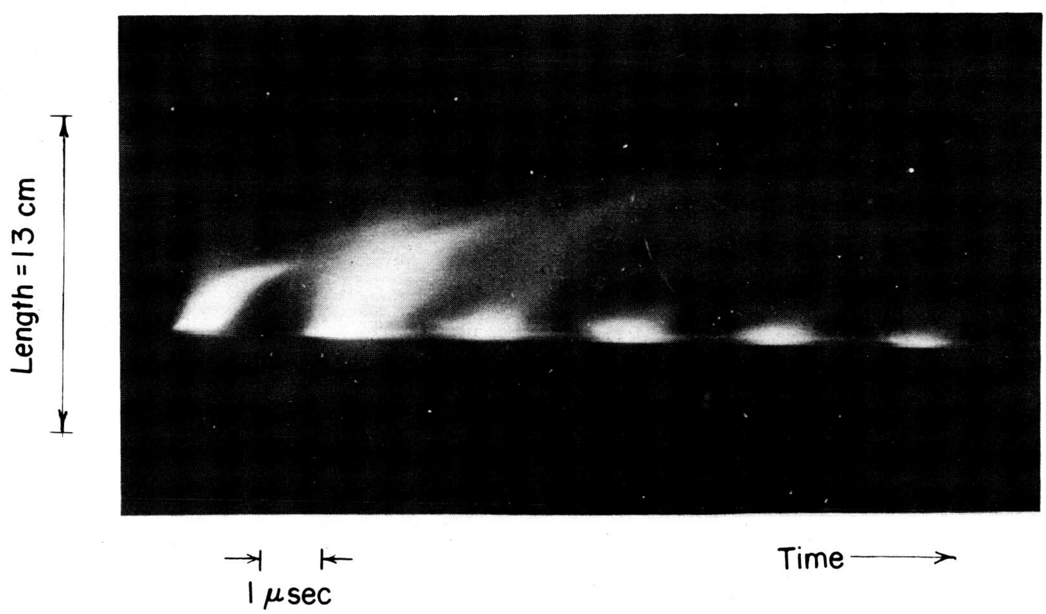
(a) Flat coil; tank pressure, 600 μ Hg.

(b) Three-turn coil; tank pressure, 200 μ Hg.

Figure 8.- End view of two plasma pulses from discharges in induced emf plasma accelerator.

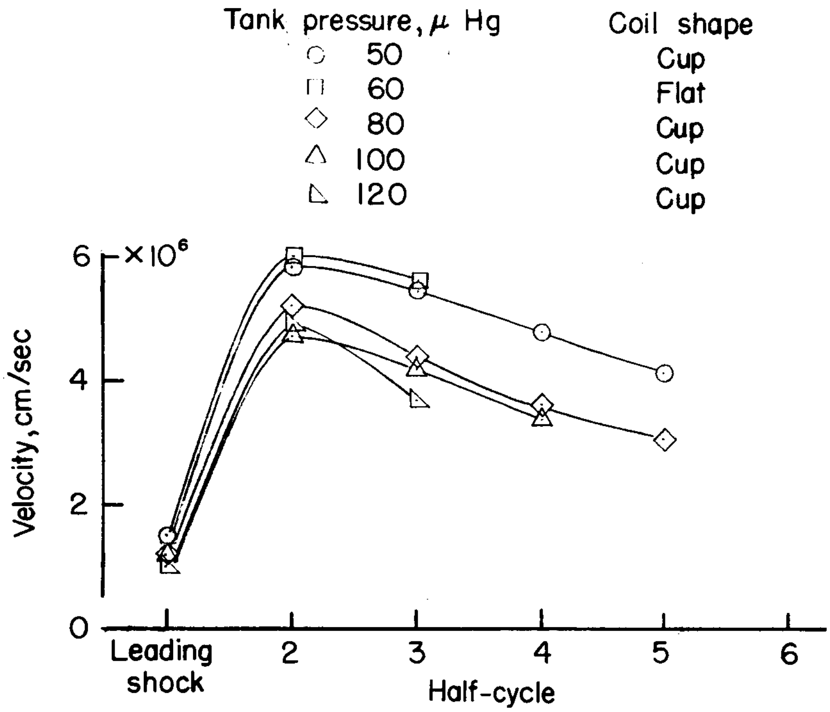


(a) Cup coil; pressure, 80 μ Hg.

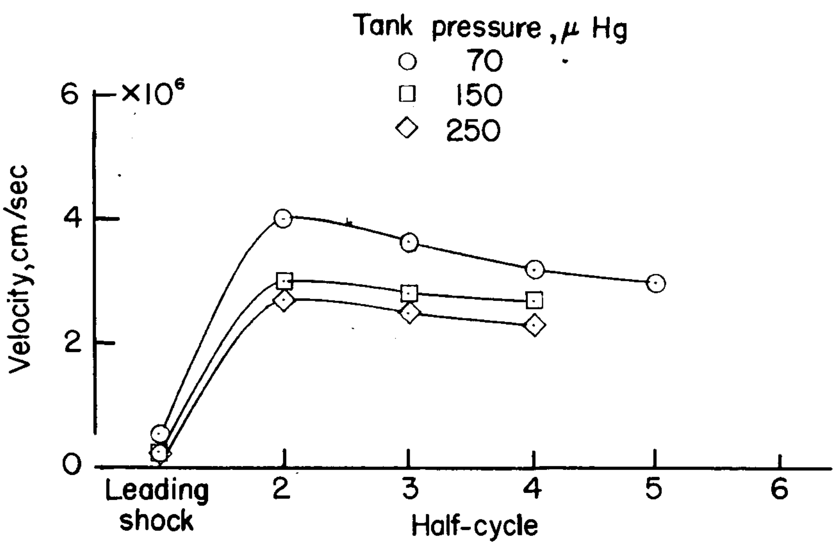


(b) Three-turn coil; pressure, 70 μ Hg. L-60-5595

Figure 9.- Rotating-mirror photographs of moving plasma.

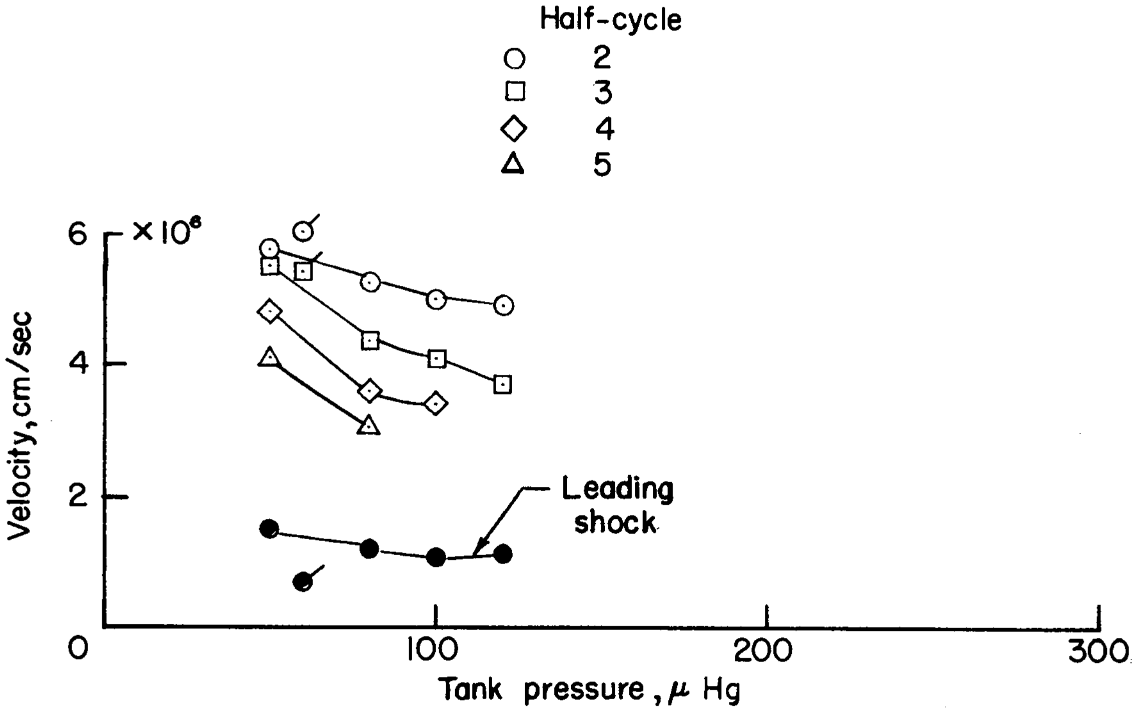


(a) Three-turn drive coil.

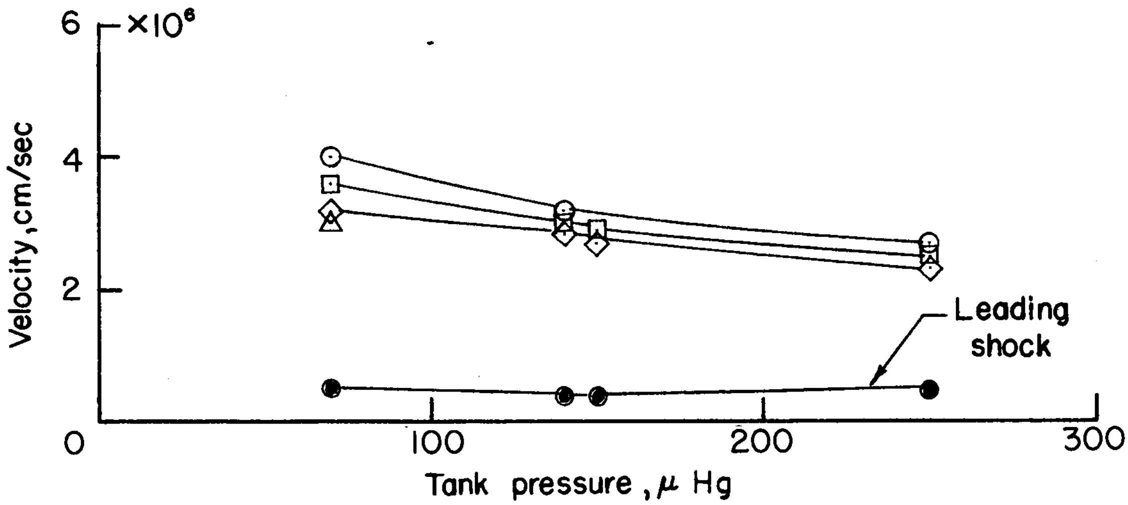


(b) Single-turn drive coil.

Figure 10.- Pulse velocities derived from streak photographs for various tank pressures and coil shapes.



(a) Three-turn drive coil.



(b) Single-turn drive coil.

Figure 11.- Variation of velocity of the plasma ring with initial gas pressure. (Plain symbols indicate cup coil; flagged symbols indicate flat coil.)