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NASA TN D-716

TECHNICAL NOTE

D-716

AN EXPERIMENTAL STUDY OF CONTINUOUS PLASMA FLOWS DRIVEN BY A CONFINED ARC IN A TRANSVERSE MAGNETIC FIELD

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON
March 1961

590678
26p.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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SUMMARY

A crossed-field, continuous-flow plasma accelerator has been built and operated. The highest measured velocity of the flow, which was driven by the interaction of the electric and magnetic fields, was about 500 meters per second. Some of the problems discussed are ion slip, stability and uniformity of the discharge, effect of the magnetic field on electron emission, use of preionization, and electrode contamination.

INTRODUCTION

One of the important problems of applied fluid mechanics is that of producing continuous gas flows at velocities higher than those obtainable with conventional gas-flow systems. One method that is being investigated for producing such a flow is that of ionizing the gas and then accelerating the resulting conducting gas by electromagnetic forces in a manner somewhat similar to the operation of an electric motor. Some investigators have proposed that such a plasma accelerator could be used for aerodynamic and reentry testing (ref. 1) and for propulsion of space vehicles (ref. 2). The possibility of producing high stagnation temperatures by acceleration at nearly constant static temperature suggests potential applications in materials research.

Most of the literature on magnetohydrodynamic accelerators consists of theoretical studies (for example, refs. 1, 2, and 3), but the results of these studies are of limited applicability in guiding or interpreting experimental investigations. Even the macroscopic equations governing the processes are so complex that closed-form solutions are obtainable for only a few special cases. (See, for example, ref. 3, p. 237.) The assumptions that are made in order to obtain a solution (for example, acceleration at constant static temperature) may not conform to a practical physical situation. Furthermore, some of the theoretical treatments ignore well-known, experimentally verified properties of plasmas. For example, it is often stated, or implied, that the current density in the plasma is proportional to the voltage, according to Ohm's law, with the proportionality constant (the conductivity) determined as a function of the gas temperature. Actually, in the conventional laboratory plasmas (glow and arc discharges) the current-voltage relationship is normally determined almost entirely by other factors, such as the cathode emitting mechanism, the power supply characteristic, and the current limiting properties of the external circuit (ballast resistance). (See secs. 8.1 and 8.2 of ref. 4.) Actually, the current is not dependent on the gas temperature in a low-pressure discharge (ref. 4, pp. 233 and 290).

Although published data on experimental studies of magnetohydrodynamic accelerators are as yet meager, a large number of laboratories throughout the country are now engaged in such studies. The experimental investigation described in this paper is part of an NASA effort in the area of plasma and ion acceleration and is concerned with a study of continuous plasma flows driven by a confined arc in a transverse magnetic field. The flow was produced in a channel by an anchored arc maintained normal to a magnetic field over a range of pressures and field strengths within which the "ion slip," according to the theory of reference 2, should be small. The resultant flow consisted of charged particles accelerated by the Lorentz force and of neutrals driven at approximately the same velocity by the directed momentum gained through collisions with the charged particles.

This investigation differed in several respects from earlier experiments reported in references 5 to 8. The most significant difference was the use of a self-sustained arc rather than a glow discharge (refs. 7 and 8) or hot-cathode arc (refs. 5 and 6). A broader range of currents was used and most of the experiments were conducted over a generally higher range of pressures. Whereas most of the reference experiments utilized an unconfined discharge, all the experiments reported herein were carried out with the discharge confined within a channel.

The physical arrangement used for the present study of low-density plasma acceleration may also be compared with the design proposed in reference 1 for acceleration of plasmas at higher pressures. In this reference, the use of thermal ionization was proposed, with a plasma generated by a preionization arc and then seeded with cesium; whereas, no use was made of preionization or thermal ionization in the present apparatus. In reference 1 it was further proposed that the accelerator electron current be emitted from "hot cathodes" requiring a 15-minute activation period prior to each run. In comparison, the discharge used in this study was a conventional nonconsumable-electrode, self-sustained arc operated at a low power level (400 to 5,000 watts). Finally, the design described in reference 1 would utilize a number of paired electrodes with each anode dis placed some distance downstream from its corresponding cathode; whereas, th present apparatus used a single pair of electrodes situated directly opposite each other.

SYMBOLS

A	area of face of plate, sq m
B	magnetic flux density, gausses
C_D	drag coefficient
$g = 9.8$ newtons/kg	
I	current, amp
p	pressure, mm Hg
T	temperature, $^{\circ}K$
V	velocity, m/sec
W	weight of plate, kg
ρ	gas density, kg/cu m
θ	angle of deflection of pendulum from vertical
Subscript:	
o	condition at standard temperature and pressure

APPARATUS AND PROCEDURE

Accelerator Apparatus

The first experimental apparatus that was built is shown in figure 1. Argon gas was metered into the settling chamber at a pressure of several millimeters of mercury, passed through a preionizing arc in the nozzle throat, and expanded to a supersonic Mach number (slightly less than 2) in the accelerator region. The accelerator consisted simply of a d-c arc maintained across the tube perpendicular to a magnetic field. The flow was ejected into a vacuum tank.

For reasons which are explained in a subsequent section, the problems involved in obtaining quantitative measurements with this apparatus were so severe that this accelerator design was eventually abandoned in favor of a second design. A schematic drawing and a photograph of this second apparatus are shown in figures 2 and 3, respectively. The flow tube formed a closed circuit, resembling somewhat a small-scale wind tunnel. The diameter of the duct in the accelerator region was 1 inch. The pump, operating at a relatively low capacity, was used together with a controlled argon leak to maintain a constant pressure in the system. The motion of the gas in the system due to the pump and the argon leak only (before the accelerator was turned on) was so slight that it was not detectable with the measuring apparatus used. The accelerator again consisted of a d-c arc normal to a magnetic field.

Two different power supplies were used to furnish the arc current. One supply had an open-circuit voltage of 1,200 volts and was capable of supplying a maximum current of about 4.5 amperes. The second supply had an open-circuit voltage of about 325 volts and was capable of supplying currents greater than 100 amperes at an arc voltage of about 100 volts, but the maximum current used in these experiments was 75 amperes.

An uncooled thoriated tungsten cathode was used. The anode was copper and was water cooled. Both electrodes protruded slightly into the flow tube. The magnetic pole pieces were tapered from a circular cross section of $2\frac{5}{8}$-inch diameter to rectangular faces $2\frac{5}{8}$ inches long by $\frac{1}{2}$ inch wide. The gap spacing was $1\frac{1}{2}$ inches. A typical survey of the longitudinal magnetic flux distribution in the tube is shown in figure 4. The point in figure 4 indicated by a triangle is a reference point and values of flux density in this paper are quoted with reference to this point.

Two types of electrode mounts were used. One mount was simply a 1-inch Vycor tube with 1-inch sidearms for inserting the electrodes into the tube. The other mount was made of boron nitride and had "O" ring fittings for the electrodes and Vycor tubes.

Velocity Measurement Procedure

Several methods of measuring the plasma flow velocity have been investigated, but the pendulum deflection method used by McBee (ref. 7) was the only one that was used extensively in this investigation. If the angle of deflection of a pendulum in the flow can be measured accurately and if the gas pressure and the drag coefficient for the pendulum are known and the temperature can be estimated, the velocity can be computed approximately by the following formula (ref. 7):

$$V^2 = \frac{2\rho_o W g}{C_D A}\left(\frac{T}{p}\right)\left(\frac{760}{273}\right)\frac{\sin\theta}{\cos^2\theta}$$

where

A	area of face of plate, sq m
C_D	drag coefficient
$g = 9.8$	newtons/kg
p	pressure, mm Hg
T	temperature, $^{\circ}$K
V	velocity, m/sec
W	weight of plate, kg
ρ_o	gas density at $p = 760$ mm Hg and $T = 273^{\circ}$ K
θ	angle of deflection of pendulum from vertical

The pendulums used for these measurements were made of plates of various sizes and materials. For example, brass plates of 0.167 gram, 0.692 gram, and 1.23 grams and Mycalex plates of 0.754 gram and 0.141 gram were used. The area of the face of each plate was 1 square centimeter. The usual procedure was to photograph the pendulum in the deflected position and compare this photograph with one taken before the accelerator was turned on (fig. 5) so that an exact measurement of the deflection angle could be made. Considerable caution was required in applying this technique, inasmuch as the pendulum had a strong tendency to oscillate when the arc and field were first turned on. When the photographs were taken after the accelerator had run for several seconds and the flow and pendulum angle had reached a steady state, the measurements obtained were at least self-consistent.

Some velocity measurements have also been made by using a pair of longitudinally displaced probes downstream from the accelerator to measure the rate at which fluctuations in the ionization level of the plasma were carried downstream. The drop across the resistor in each of the probe circuits was fed to one of the inputs of the oscilloscope chopper unit. With the high-frequency plasma oscillations filtered out, the 120-cycle arc ripple of the current from the full-wave rectifier supply was picked up distinctly by both probes (fig. 6). Unfortunately, this technique was successful only for the narrow range of values of current, field, and pressure which produced velocities below about 125 meters per second, inasmuch as higher velocities did not give a sufficient displacement to be measured with any degree of accuracy. However, at the lower velocities the displacement was easily measured, and the velocity measurements so obtained agreed, within about 15 percent, with those obtained by the pendulum deflection method.

RESULTS AND DISCUSSION

Sources of Error Involved in Obtaining Quantitative Velocity Measurements

A considerable effort was made to distinguish between the effect of the Lorentz force on the gas and other extraneous effects. This problem was especially severe in the initial experiments which were conducted with the apparatus shown in figure 1. No attempt was made to construct an apparatus for optimum performance.

The arc across the tube could be maintained in the presence of the flow and the magnetic field, and the arc voltage increased by about 70 percent when the field was turned on. The system gave the appearance of operating properly, but obtaining reliable and meaningful measurements of its performance proved to be extremely difficult. The use of a blowdown system is not satisfactory for operation at low stagnation pressures. The maximum running time was about 40 seconds, and the pressure in the tank was rising throughout this period. Transient pressure effects resulting from initiating the flow, striking the arc, and increasing the magnetic field occur, and considerable time is required for the pressures to reach equilibrium values at the reduced pressures used in these experiments. It was concluded that no reliable quantitative measurement of any velocity increase due to the accelerator could be obtained by means of pressure measurements.

An increase in Mach number through the accelerator could be determined by observing a change in the angle of a shock wave on a thin plate in the flow. When the accelerator was turned off, the system operated in a manner similar to a conventional supersonic plasma jet, and a shock wave could be seen on a plate mounted in the stream. When the accelerator was turned on, however, no shock wave was visible. It is possible that the flow was choked by the rise in static temperature in the accelerator arc. However, the intensity of the light from the accelerator arc was so strong that, even if a shock wave had existed, it probably could not have been visibly distinguished.

One measurement that can be made readily is that of the amount of energy introduced into the flow by the arc, as was done in reference 9. However, this measurement alone is not sufficient to determine whether the flow has been accelerated, since some of the power goes into heating the flow; this heating tends to lower the velocity and Mach number in a supersonic flow and therefore counteracts some of the accelerating effect of the crossed fields.

The problem of distinguishing between the effect of the electromagnetic force and that of the superimposed flow was eliminated in the device shown in figure 2, since there was no flow until the accelerator was turned on. Various experiments were designed to determine whether the accelerator was actually performing as it was intended - that is, whether it was exerting a continuous electromagnetic pressure on the neutral gas. For example, the deflection of a brass pendulum hung in the flow could be increased by holding either the current or field strength constant while increasing the other quantity. (See fig. 7.) In order to determine whether the deflection of the metal pendulum was due to eddy currents produced by the fluctuations in the arc, the experiments were repeated with a Mycalex pendulum. It may be possible that an insulator hung in a low-density plasma can be deflected by some action similar to an electroscope effect because of the charge on the insulator resulting from the inequality in electron and ion diffusion rates. It may also be possible for a transient flow to be produced by thermal expansion if the arc heats the gas considerably. In order to verify that the pendulum deflection was not due to either of these effects, the accelerator was run in the reverse direction - that is, with the magnetic poles reversed so that the arc deflection and the gas flow were away from the pendulum. The pendulum would then be blown forward by the flow which, having circulated around the entire system, was thoroughly deionized (fig. 8).

However, when the system was operated at the higher currents (above about 30 amperes), the flow did not always result solely from the electromagnetic force. Immediately downstream from the electrodes the current had a considerable longitudinal component so that the force on the positive column in this region tended to press it against the wall. The resultant heating of these wall areas caused the wall temperature to rise so rapidly that after about 10 seconds of operation a considerable amount of the wall material was vaporized. This action would generate a vapor pressure of several millimeters. This vaporization of wall material, together with the subsequent thermal expansion, caused the arc region to behave as a strong gas source. Under these conditions, the arc was still deflected downstream (in the amperian direction) and the glowing plasma, as well as glowing bits of eroded wall material, then could be seen streaming in this direction, but a pendulum hung in the flow ahead of the accelerator would then (that is, after the arc had been operating for about 10 seconds) swing backward, this action indicating that there was a flow outward in both directions from the accelerator region.

Another extraneous effect which may become significant at the higher currents is the acceleration of the plasma away from highly constricted regions of the arc as a result of a nonuniform squeezing of the arc by its own magnetic field. (See ref. 10, sec. 94.) The occurrence of this action in the presence of an externally imposed magnetic field apparently has not yet been demonstrated but, if this action does occur, it should become significant at currents higher than about 50 amperes at the pressures used in these experiments, according to the equations in reference 10, and then only if there is a strong constriction of the arc. For example, this action should not occur at the cathode in these experiments, since the emission at currents above 30 amperes is not from a small spot (ref. 10, fig. 84); however, since there is a constriction at the anode, this effect may become significant when the accelerator is operated at currents above 50 amperes. Since the current direction in the immediate vicinity of the anode is almost entirely longitudinal, this action, if it occurs, should contribute to the acceleration.

Observed Behavior of an Arc in a Transverse Field

For these studies of continuous gas flows driven electromagnetically, self-sustained discharges were used exclusively. The use of glow discharges and hot-cathode arcs in this context has already been investigated by University of Michigan scientists (refs. 5 to 8). The currents that are practically obtainable by these methods are limited, however; whereas, self-sustained arcs have been operated at currents of hundreds of amperes, even at reduced pressures (ref. 11). Even the low-current studies (2 to 5 amperes) were made with self-sustained arcs so that the operation of the accelerator at these lower currents would be qualitatively similar to its operation at higher currents.

The experiments with glow discharges and hot-cathode arcs reported in references 5 to 8 indicate that the presence of the magnetic field caused large-amplitude fluctuations in the discharge. In the present experiments with self-sustained arcs, no increase in the arc fluctuations was observed when the magnetic field was turned on. As the current was increased, the amplitude of the fluctuations decreased and the discharge operated relatively smoothly at currents of 50 amperes and higher.

Luce (ref. 11) has pointed out that the cathode should tend to emit electrons along the field lines rather than across them. In the present experiments, it was not possible to observe the cathode directly, but traces left by a low-current (3 amperes) arc spot on a copper cathode indicated that the spot was localized on the downstream edge of the cathode in the presence of the magnetic field. When the 1/8-inch thoriated tungsten cathode was used at the higher currents (greater than 30 amperes), the entire end of the cathode became sufficiently heated to emit electrons and there was no evidence of spot formation. In either case, no difficulty was experienced in striking or maintaining the arc other than that which would normally be expected as a result of the lengthening of the arc column, the loss of ionized particles due to the contact of the arc with the wall, and the loss of ionized particles to the flow.

One of the problems encountered in any plasma flow system that utilizes a discharge in the stream for the production of plasma is the possible adulteration of the gas by vaporized or eroded electrode material. Since the gas is already at reduced pressure, even a very low rate of metal vaporization is sufficient to cause the mass ratio of the vapor to the pure gas to become significant and possibly to become quite high. It was found, however, that with the thoriated tungsten cathode and water-cooled copper anode the observed loss of electrode material was so slight that the ratio of the mass flow of electrode material to that of the gas was insignificant. This result is not surprising, inasmuch as refractory metal cathodes are commonly used to minimize the loss of electrode material. It has been found, for example, that there is no significant consumption of a molybdenum cathode in an arc operated at power levels up to 30 kilowatts (ref. 12). At reasonable power levels, no melting of the anode should occur so long as a sufficient flow of cooling water is maintained. At high power levels, however, it is possible that the anode will be perforated by the arc (ref. 13). The possibility of perforation may be greater when an anchored arc is operated normal to a magnetic field because the anode end of the arc is then localized on the downstream edge of the anode.

Another consideration that deserves attention is the degree of uniformity of the current distribution in the discharge. At pressures near atmospheric, an arc tends to be thermally constricted but, when the pressure is reduced below 100 mm Hg, it becomes much more diffuse (ref. 12). At a pressure of 50 microns Hg a high-current argon arc may spread out to a diameter of several feet, whereas at a somewhat lower pressure the arc again becomes constricted, apparently because of the effect of its self-magnetic field (ref. 11). Even when the plasma accelerator is operated over a pressure range in which the arc is diffuse (as, in these experiments, 0.25 to 10 mm Hg), the ends of the arc are constricted since the arc tends to anchor on the downstream edges of the electrodes. From visual observation of the arc itself and the observed corrosion of the accelerator walls downstream from the electrode, the positive column of the arc was found to be somewhat U-shaped. The column was pressed strongly against the wall near the electrodes but spread out as it was deflected downstream and became quite diffuse as it crossed the flow. At the higher pressures, low currents, and low values of magnetic flux density, a discrete arc region extending several inches downstream from the electrodes could be seen (fig. 9); however, as the pressure was reduced and the field was increased, the light from the plasma decreased in intensity and became more uniformly distributed throughout the visible region of the flow (about 8 inches downstream from the electrodes) so that a discrete arc region was no longer apparent.

Even when the arc is not thermally or magnetically constricted, a high degree of uniformity in the current density distribution cannot be expected because of the ionization gradient resulting from such effects as diffusion and the cumulative action of metastable ionization (ref. 14). The gas should experience little acceleration near the top and bottom walls where the degree of ionization is low. However, a theoretical concept of absolutely uniform ionization and velocity profiles implies difficulties with wall heating due to intimate contact of the wall with the intense plasma and the high-velocity flow, as well as with the practical problems involved in the realization of such profiles.

An auxiliary discharge upstream from the accelerator is a logical component of a plasma accelerator, inasmuch as such a discharge should supply a sufficient degree of ionization to help start the accelerator current and maintain it in the presence of the flow and the magnetic field. Since, with such preionization, the accelerator discharge does not have to provide the extra power to replace the ionized particles lost to the flow, the arc should operate at a lower voltage, and thereby the power supply requirements should be eased somewhat. In some of the experiments an auxiliary discharge was produced in the flow by a radio-frequency coil around the tube upstream from the accelerator. The current was coupled capacitatively into the gas by the high-frequency field. (See ref. 15.) The electron density produced in the region of the electrodes was somewhat higher than 10^{10} per cubic centimeter, as measured with positive-ion saturated probes (ref. 16). This discharge, however, had virtually no effect either on striking the arc or on the voltage drop across the arc in the presence of the field, and the use of this auxiliary discharge was therefore discontinued.

As might be expected, the arc had a rising characteristic when operated in the presence of the magnetic field. For example, with a brass cathode at a pressure of 3 mm Hg in argon, the arc voltage increased about 10 percent when the current was increased from 3 to 4 amperes.

Velocity Measurements

The pendulum deflection method of measuring velocities cannot be expected to give an exact indication of the absolute velocity because of possible errors involved in estimating the temperature and drag coefficient; however, when reasonable caution is exercised, this method provides a self-consistent basis for comparing the effects of varying the different plasma parameters. The effect of varying the current while holding the pressure and field strength constant is shown in figure 7(a) for one value of pressure and field strength. The effect of varying the magnetic field strength at constant pressure and current is shown in figure 7(b) for one value of pressure and current. Notice that when a curve is faired through the experimental points, the velocity indicated for the conditions $p = 3.0$ mm Hg, $I = 3.2$ amperes, and $B = 5{,}500$ gausses in figure 7(a) is about 160 meters per second, whereas the velocity indicated in figure 7(b) for the same conditions is about 152 meters per second. Thus, the two independent measurements check each other with a reasonable degree of accuracy. It would not be safe to assume that curves similar to those shown in figure 7 would necessarily be obtained with a different set of constant conditions (these curves are somewhat dissimilar in form to those obtained by McBee (ref. 7) at lower currents and pressures) or that they could be extrapolated to higher currents or field strengths.

No attempt has been made to determine the precise variation of velocity as a function of pressure, since the variation of temperature over the pressure range in which the experiments were conducted was not known. However, one of the most notable results of the pendulum-deflection studies was the marked increase in the deflection angle when the pressure was raised from 1 to 10 mm Hg while the current and field strength were held constant. In fact, if the arc temperatures given in reference 4 (p. 290) for this pressure range are assumed for the velocity computations, the results indicate that the velocity decreased only slightly when the pressure was increased through this range. This effect is not fully understood, inasmuch as many factors other than the temperature rise have to be considered in analyzing the effects of raising the pressure.

For example, with a current of 3 amperes the voltage increased 25 percent when the pressure was raised from 2 to 10 mm Hg, but it is difficult to estimate how much, if any, of the additional power is utilized in accelerating the gas. Part of the additional power may have been used in maintaining the ionization level, if the deionization processes were more effective at the higher pressures (ref. 4, sec. 9.6). However, one could argue qualitatively that the effectiveness of deionization processes should not be significantly augmented as the pressure is raised from 2 to 10 mm Hg, since three-body recombination should be a relatively small effect at these pressures, radiative recombination is not pressure dependent, and deionization at the wall (diffusion loss) actually decreases.

A further consideration is that the accelerator may operate more effectively at the higher pressures because the charged particles have more momentum-transfer collisions while they are being accelerated in the field.

Finally, since the Reynolds number appears to be higher at the higher pressures, there may be a reduction in friction loss due to the higher Reynolds number operation.

The difficulties in obtaining absolute velocity measurements by the pendulum deflection method have been discussed by McBee (ref. 7). Besides the error involved in the assumption of a drag coefficient of 1 for the pendulum, a further possible error is introduced by estimating the temperature value from figure 9.1 in reference 4 rather than by measuring it directly. Although the velocity varies only as the square root of the gas temperature, it is impossible even to compare velocity measurements made by this method unless some consistent basis is used for estimating the temperature. In experiments with glow discharges, McBee originally (ref. 7) estimated a temperature of 570° K and computed a maximum velocity of about 300 miles per hour (134 m/sec), but in a later report of the same work (ref. 8) he quoted velocity values roughly three times as high (315 m/sec), apparently as a result of an order-of-magnitude increase in temperature estimate. Furthermore, arguments have been given for using temperature values of 8,000° K or higher for computing velocities in the glow-discharge accelerator. (See ref. 8, Discussion, pp. 237-238.) However, when no magnetic field is present, the temperature in the glow discharge column is normally less than 100° C (ref. 4, p. 233) and the assumption of extreme temperatures does not appear to be justified unless it can be demonstrated that the presence of the magnetic field results in a much more efficient heating mechanism in a low-pressure discharge than that which exists in the discharge without a magnetic field.

The temperature of an arc discharge is a very strong function of the pressure over the pressure range from 1 to 10 mm Hg (ref. 4, p. 290), and the assumed temperature of 1,000° K at 3 mm Hg is roughly consistent with the values given in reference 4 (p. 290), although this estimate is believed to be somewhat high because of the cooling effect of the continuous flow through the discharge. However, the error introduced into the velocity computation should not be too severe, since the velocity varies only as the square root of the gas temperature. The temperature of an arc column depends very weakly on the current (at low currents) even at atmospheric pressure (ref. 4, p. 327).

When the velocities obtained from the pendulum-deflection measurements were compared with those made with longitudinally displaced probes in the stream at the lower field strength, it was found that the velocities measured with the probes were roughly 15 percent lower. Since the probes detect the velocity of the charged particles, this result indicates that the effect of ion slip was small, and possibly negligible, at a pressure of 3 mm Hg and a flux density of 3,000 gausses. Furthermore, since the velocities computed from the pendulum-deflection measurements appear to be too high, this discrepancy indicates that the temperature estimate of 1,000° K is probably an overestimate by roughly 30 percent.

As has already been mentioned, it is difficult to measure the velocity produced by the electromagnetic force when the accelerator is operated at currents so high that the wall vaporizes and therefore acts as a pressure source. Several measurements were made with accelerator arc currents of 30 to 40 amperes and field strengths of 2,000 to 4,000 gausses. Every effort was made to obtain the measurement before the wall became hot enough to vaporize. After a number of records were compared, it was concluded that the highest steady velocity produced before wall vaporization became significant was in the neighborhood of 500 meters per second. This velocity represents, of course, a fairly high subsonic Mach number at the temperature assumed.

CONCLUDING REMARKS

A gas flow has been produced in a closed-circuit duct and driven to velocities up to about 500 meters per second by a confined d-c arc in a transverse magnetic field. For a given set of experimental conditions, the velocity increased approximately linearly with increasing current. The velocity also increased with increasing magnetic flux density when the current was held constant, but the variation was linear only over a restricted range of values of the field strength. The positive column of the arc was not thermally constricted, but was relatively diffuse over the range of pressures studied (0.25 to 10 mm Hg). At the power levels used, the loss of material from the thoriated tungsten cathode and water-cooled copper anode was negligible. The pendulum deflection method of measuring velocity was found to be self-consistent and provided a reasonable basis for comparing velocity measurements when the temperature could be assumed constant. It appears that the basic design used can be extended to operate at somewhat higher currents and field strengths, provided sufficient cooling is supplied to prevent wall vaporization.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Field, Va., December 12, 1960.

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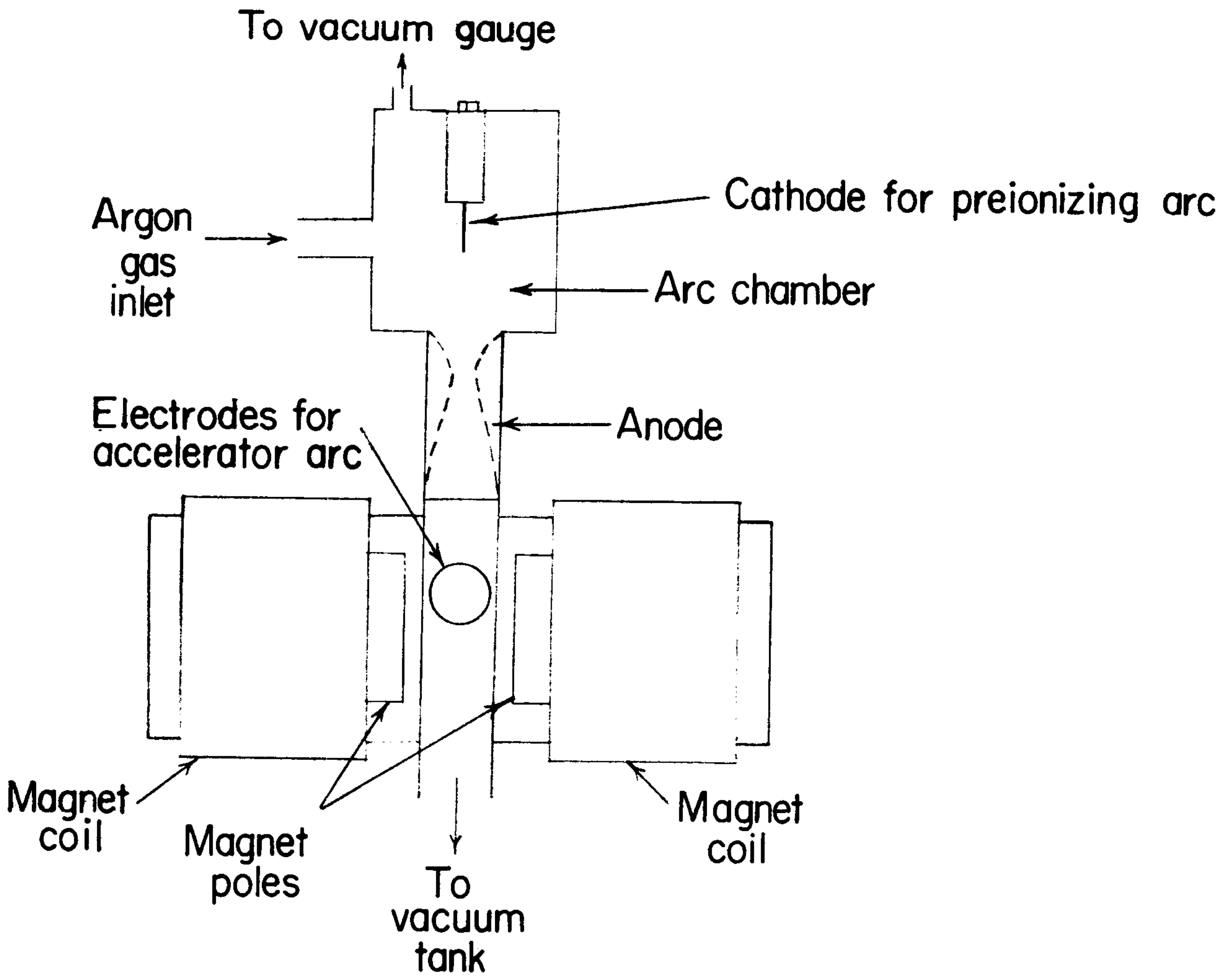


Figure 1.- Schematic diagram of first apparatus for plasma-acceleration studies.

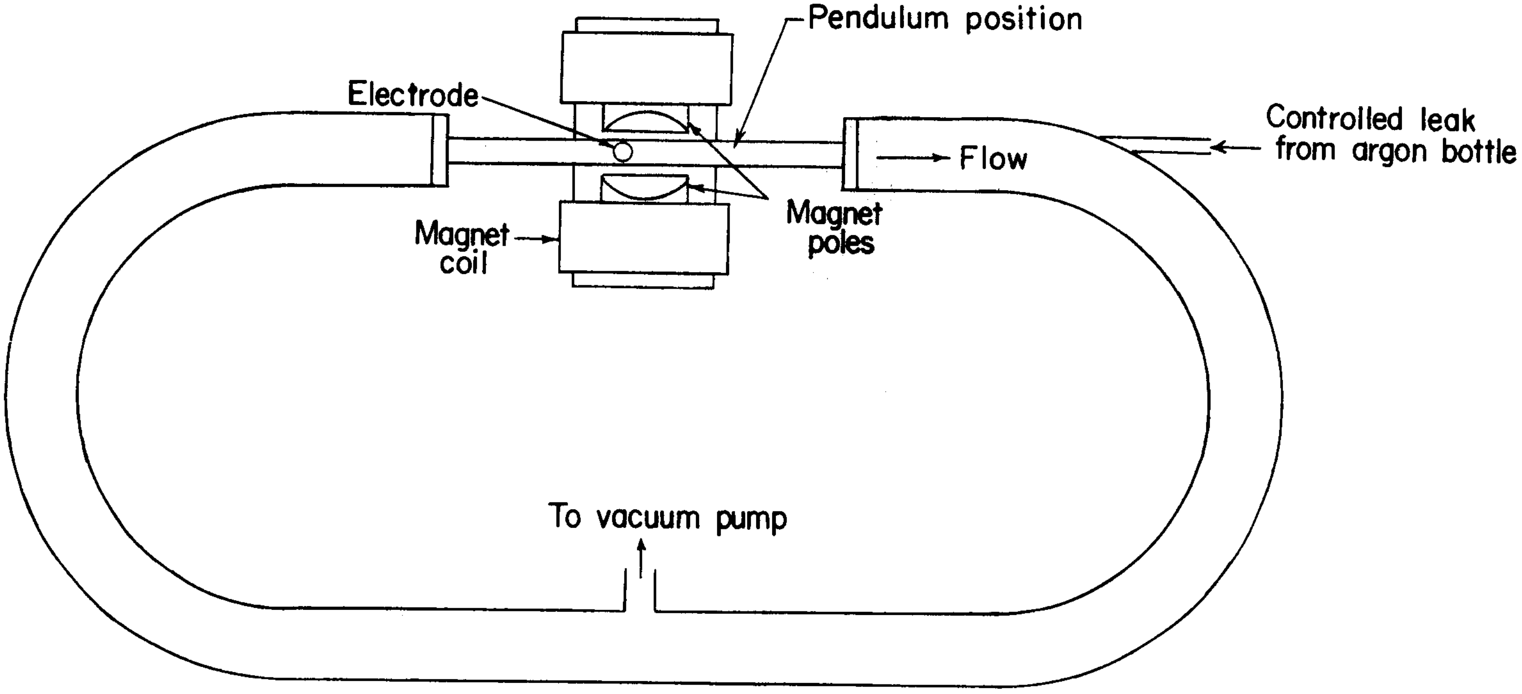


Figure 2.- Schematic diagram of second plasma-acceleration research apparatus.

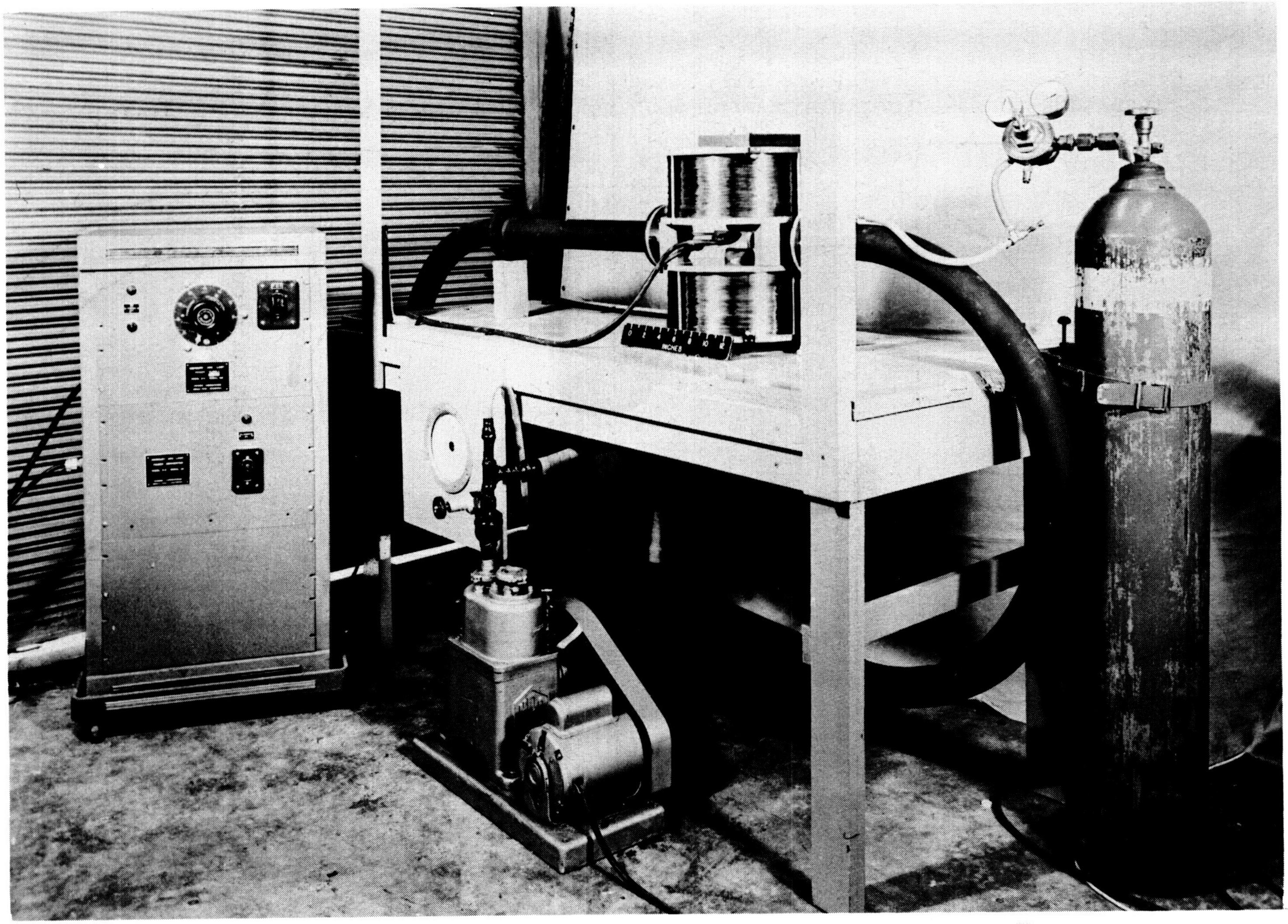


Figure 3.- Second plasma-acceleration research apparatus. L-60-7021

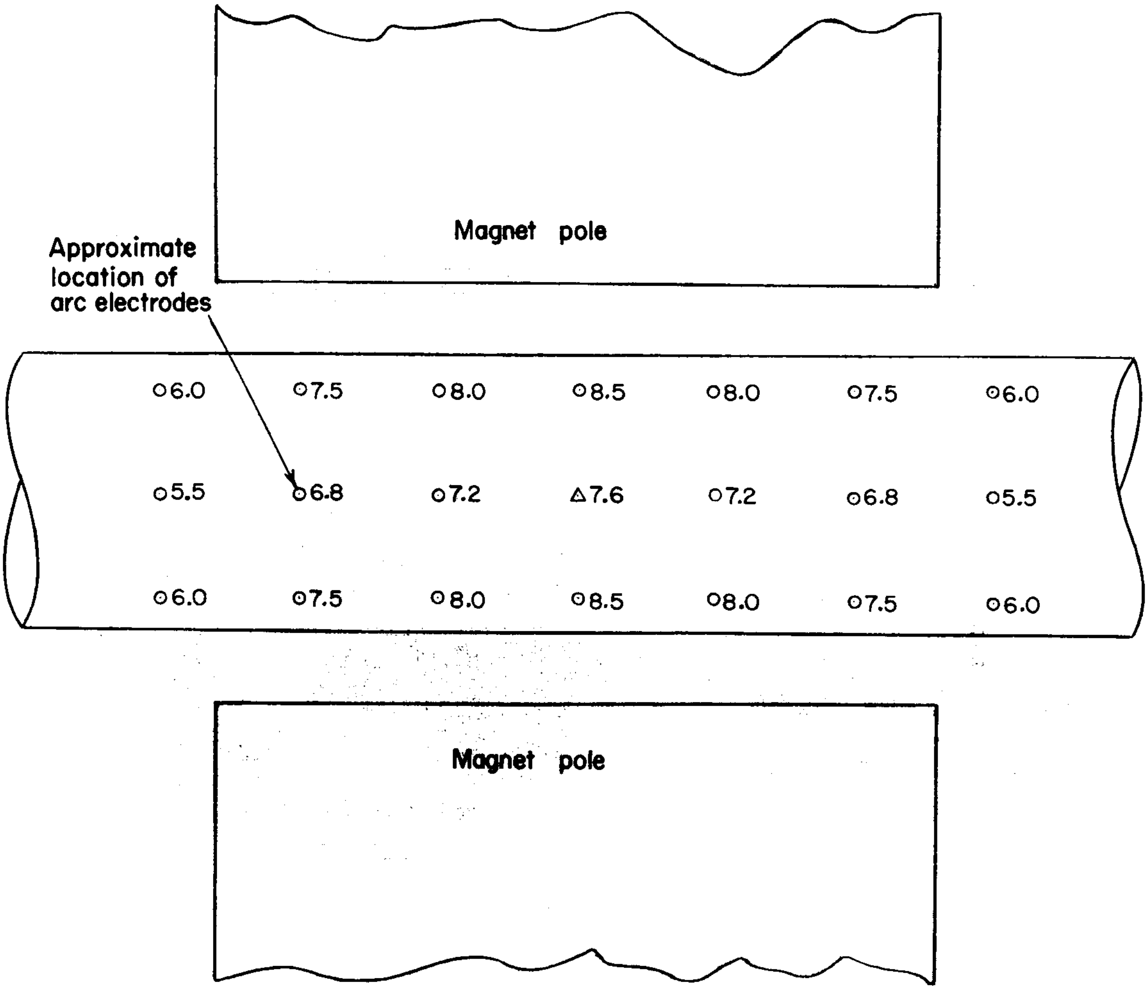
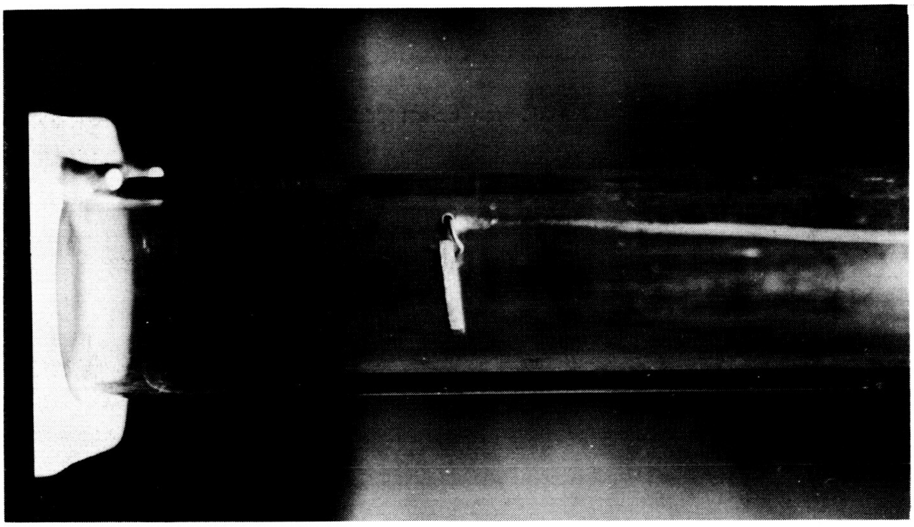
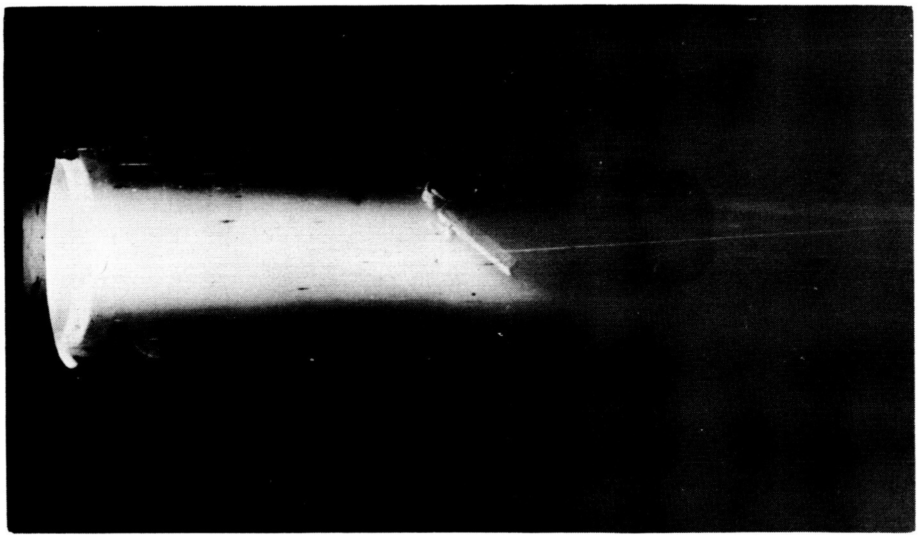


Figure 4.- Typical magnetic flux distribution along center plane of duct. Units in kilogausses.



(a) Without flow.



(b) With flow.

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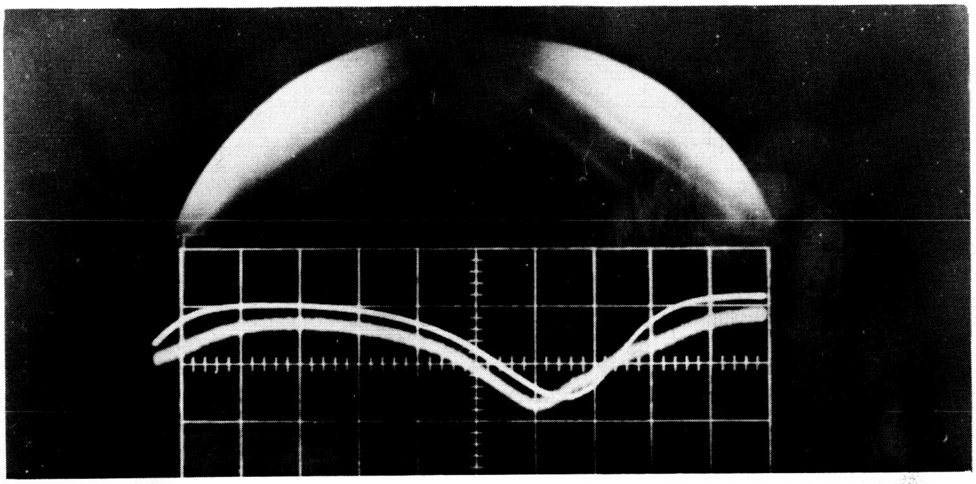
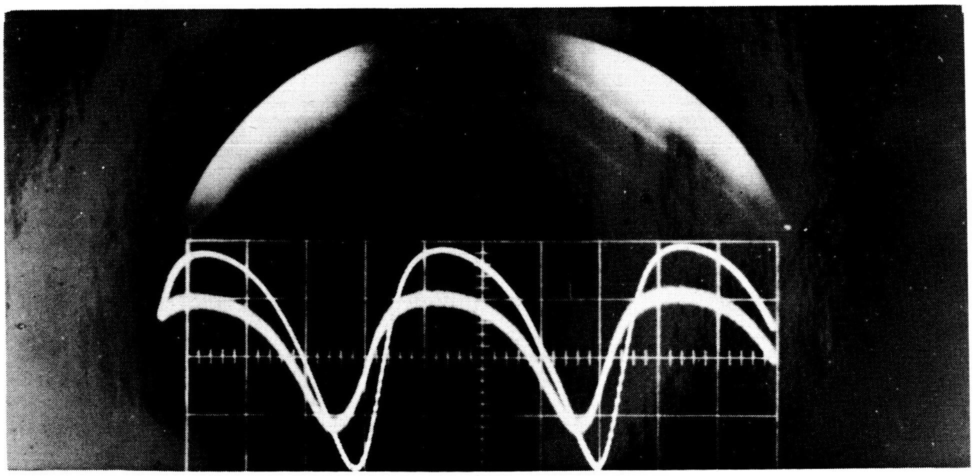
Figure 5.- Comparison of pendulum position without flow and with flow.



(a) Oscilloscope sweep rate, 1 millisecond per centimeter.



(b) Oscilloscope sweep rate, 2 milliseconds per centimeter.

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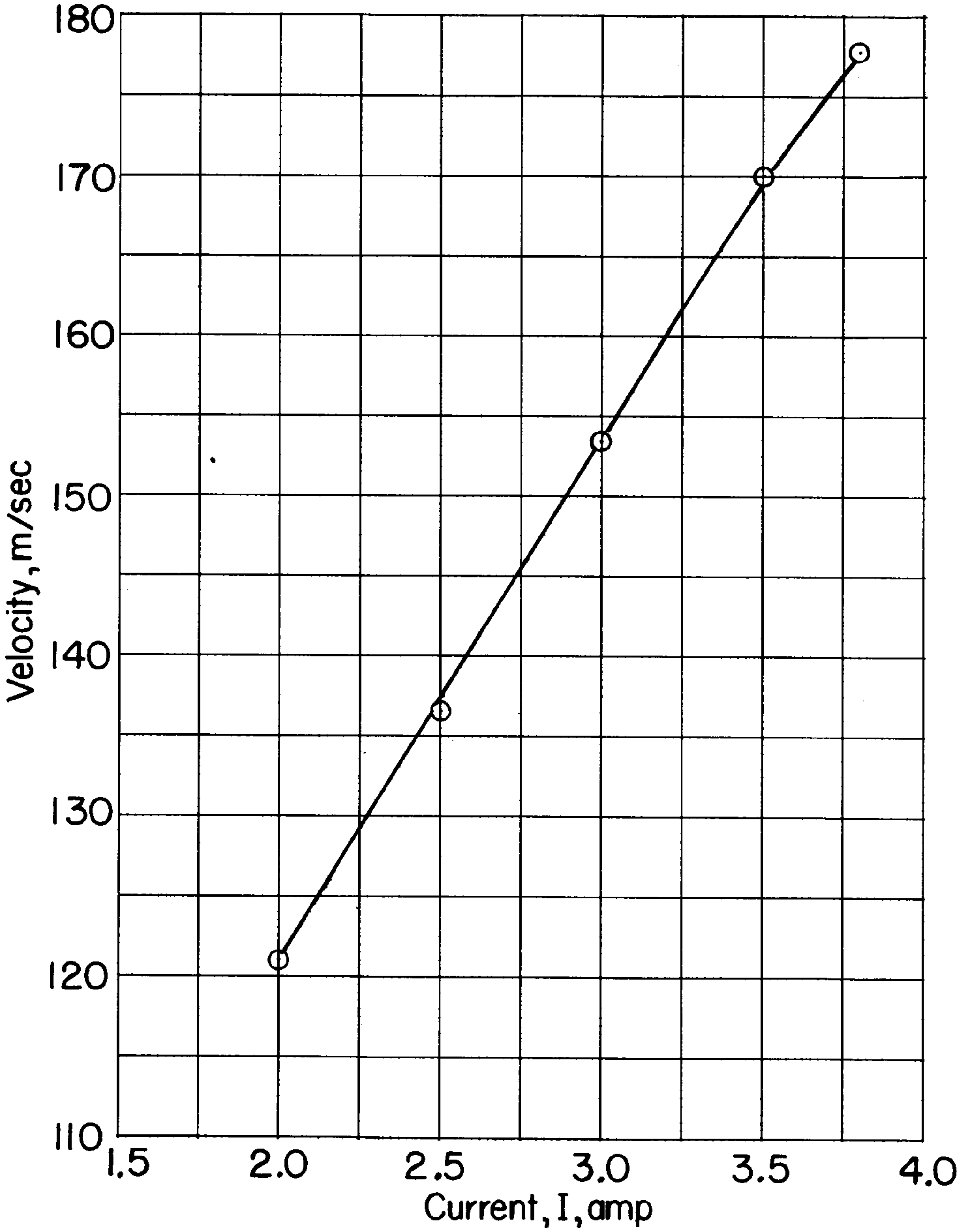
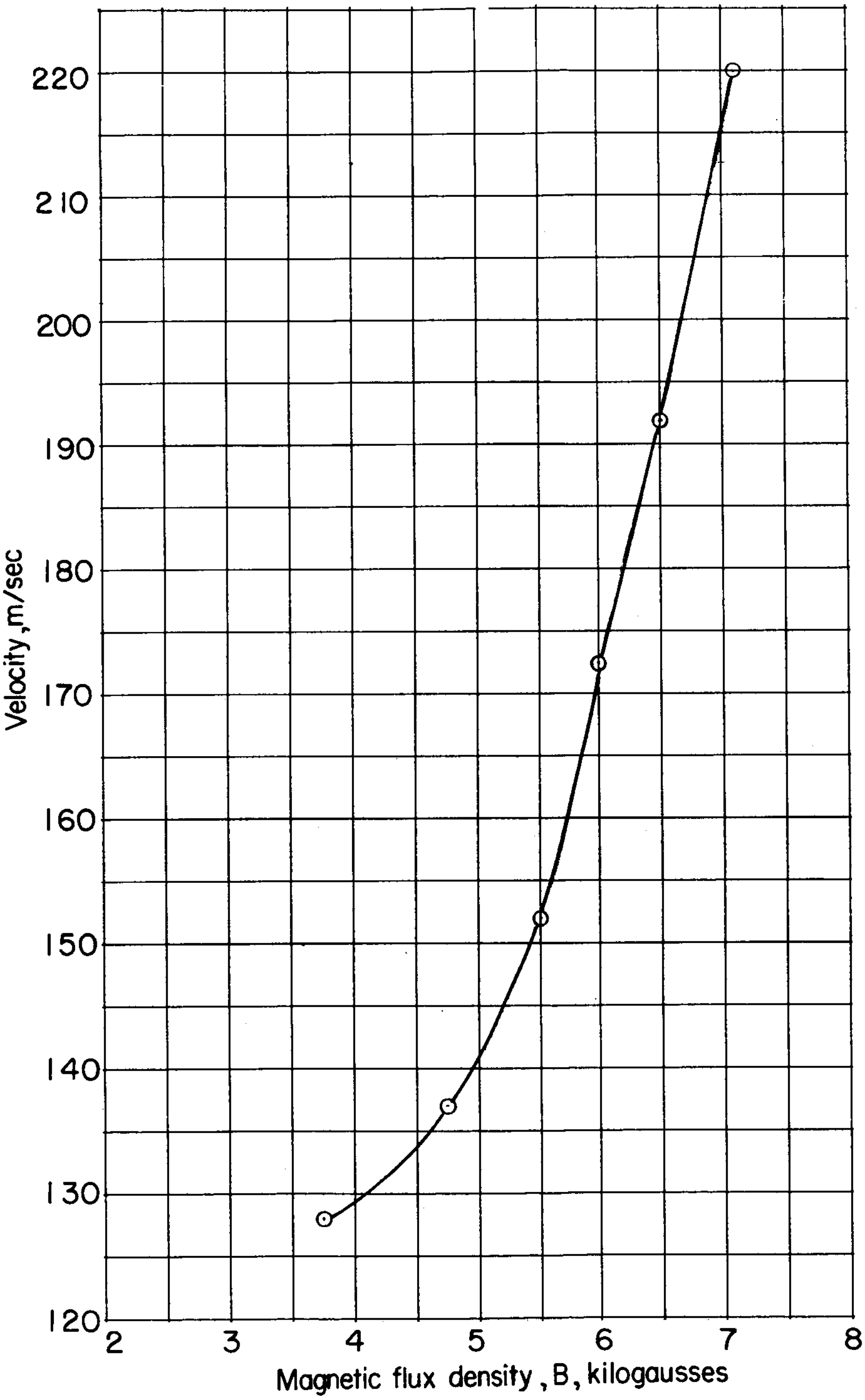
Figure 6.- Oscilloscope traces of the currents to two longitudinally displaced probes in the flow.



(a) Variation of velocity with current for $p = 3.0$ mm Hg, $B = 5{,}500$ gausses, and $T = 1{,}000^{\circ}$ K (estimated).

Figure 7.- Typical results of pendulum deflection velocity measurements in argon.



(b) Variation of velocity with field strength for $p = 3.0$ mm Hg, $I = 3.2$ amperes, and $T = 1{,}000^\circ$ K.

Figure 7.- Concluded.

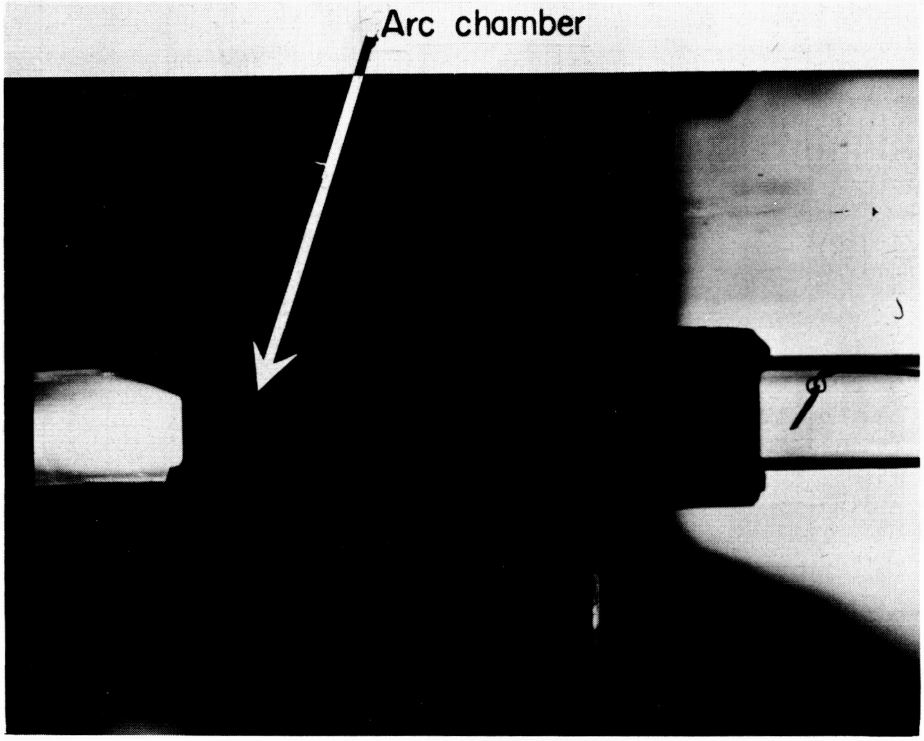


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Figure 8.- Forward deflection of pendulum by neutral gas flow with accelerator in reverse operation.

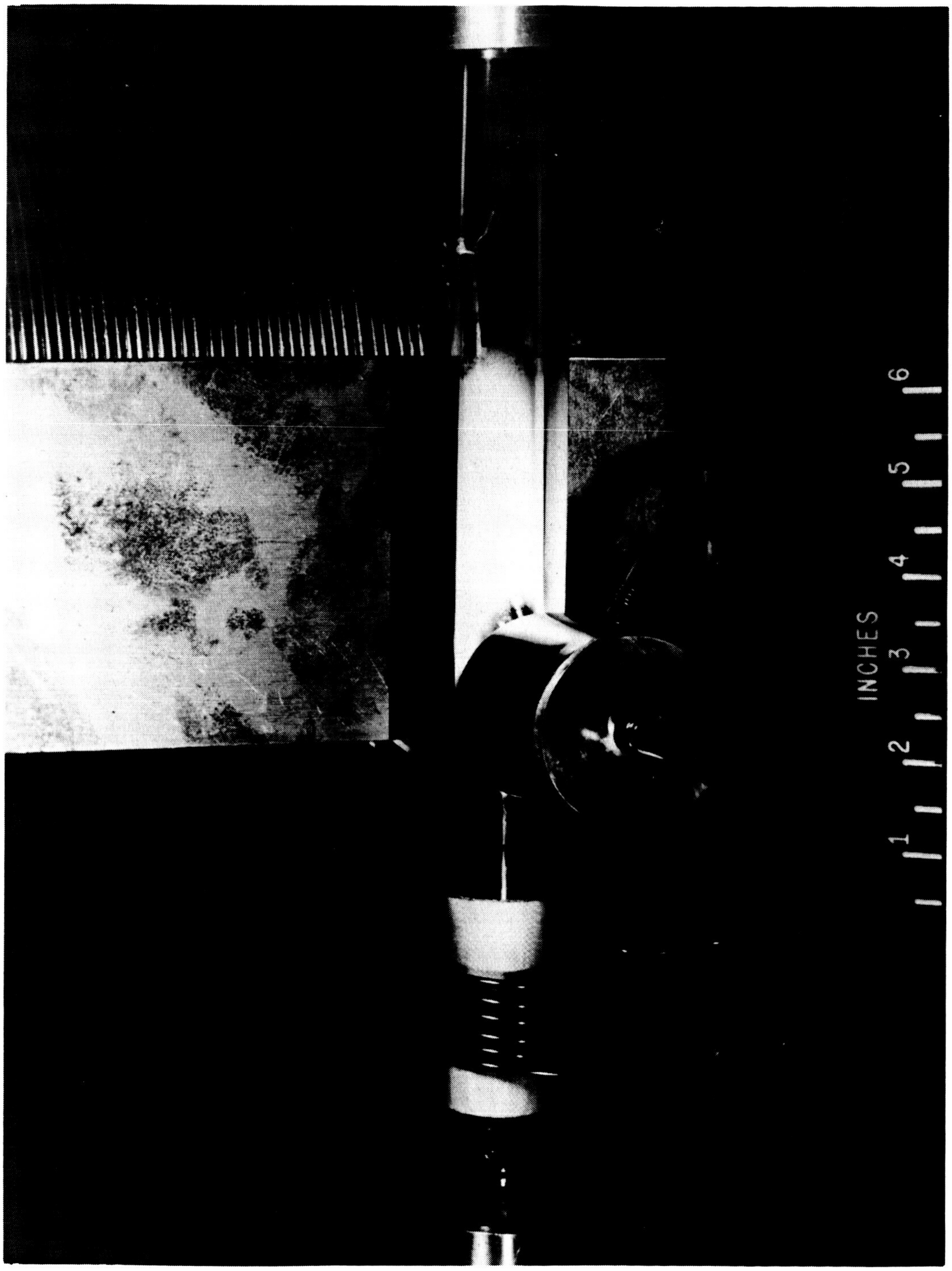

Figure 9.- A confined arc in a transverse magnetic field. L-60-2881