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Introduction

The major reason for studying the performance of the MPD arc using various propellants and propellant mixtures is to determine whether a mixture of ions and neutrals can be efficiently accelerated to high velocities, thus saving energy expenditure in ionization. The indication that this may be possible is obtained from velocity measurements at other laboratories based on thrust and mass flow. These measurements, however, have been under question because of possible entrainment of gas in the vacuum tank and of interference with the tank walls. The problem of acceleration of neutrals by ions enters also strongly into several theoretical models involving "critical mass flows"[1,2] in which it is assumed that the neutrals are not properly utilized since they are not accelerated by the ions.

The purpose of this study is to evaluate these problems by performing independent measurements of the velocities of ions and neutrals and by observing other changes in the arc and plasma jet characteristics as the propellant mixtures are changed and parameters like total mass flow, current, and magnetic field are varied. For this purpose velocity measurements are performed using the spectroscopic method of Doppler shift, and time-of-flight methods using the propagation of natural disturbances in the plasma jet. The differences between the propagation of fluctuations in ion density, potential, and light are evaluated. These velocity measurements are compared with those obtained from thrust and mass flow for various gas mixtures, currents, and magnetic fields.

The distribution of electric fields in the plasma jet is also studied including steady as well as fluctuating components and its dependence on propellant mixtures and the other parameters.

Apparatus

A schematic of the apparatus is shown in figure 1. The cathode is 1.27-cm diameter 2-percent thoriated tungsten and 1 inch is exposed to the discharge. The copper anode is 1.9-cm i.d. on the upstream end and 2.54-cm i.d. downstream. The exposed face downstream is 2.54 cm i.d. and 3.18 cm o.d. The insulators are made of boron nitride. The discharge exhausts into one end of a nonmagnetic stainless-steel tank 1.8 meters in diameter and 4.5 meters long. The magnetic field is generated by a solenoid, and a typical magnetic field configuration showing lines of constant axial and radial field is given in figure 2. Magnetic fields given in this paper are measured at the tip of the cathode. The vacuum system operates below 10^{-3} torr for all mass flows reported here. Tests have been performed in ammonia, nitrogen, hydrogen, argon, and deuterium, as well as in nitrogen-hydrogen mixtures. Currents were from 100 to 500 amps and magnetic fields 3000 and 6000 gauss.

Velocity Measurements

Measurements of Velocity Using Correlation of Fluctuations

Measurements of arc jet velocities have been obtained by use of correlations of axially and azimuthally propagating coherent fluctuations. The propagation of fluctuations of the three quantities of potential, ion flux, and light emission has been observed in order to measure axial velocity, with the probes carefully alined along the geometric axis of the arc. Frequencies were filtered as required to permit clearer presentation of the coherent fluctuations on a two-beam oscilloscope. Phase or time difference of the propagating disturbances, together with the known axial displacement of the probes, was used to determine velocity by this time-of-flight technique.

The light fluctuation measurements were performed with an optical system using two photocell stations, as in reference 3, but with a 8.9 cm f.5 lens, which gave resolutions of 1.5-mm diameter and 0.75-mm depth of field (measured at half-intensity). Extremely high velocities were measured using this system. Figure 3 shows the output of two photocells recorded on a dual beam oscilloscope. The first photocell measured light at a point 12.5 cm axially from the anode face; the second at a point 32.5 cm downstream, a time lag of 2.5 microseconds between the two points 20 cm apart gives a velocity of 8×10^4 meters/sec. This was for ammonia, at 0.01 g/sec mass flow, 6000 gauss magnetic field, and 600 amperes. Values obtained with light fluctuations for other propellant mixtures and flow parameters also indicated unreasonably high velocities. It was concluded that rather than flow of the jet, they might represent excitation regions produced by electron currents in the plasma jet, or some other high-velocity perturbations.

Velocity measurements using Langmuir probes biased to give ion flux perturbations were also taken at the same distance. A typical measurement, shown in figure 4, gave lower values of velocity; these values were comparable to velocities based on thrust and mass flow measurements. A few potential fluctuation measurements with floating Langmuir probes, using the same presentation, achieved velocities more like the light fluctuation results, suggesting an association between electron flow disturbances and light production.

Measurements of azimuthal velocities of perturbations were performed by using a pair of probes at 90° azimuthal separation, biased to measure ion flux. No rotational effect was found for argon at 22.5 cm from the anode, but definite evidence of a rotational perturbation existed at 6.25 cm from the anode. Since electric fields appear at these distances the rotational fluctuation and electric fields appear to be associated.

At the lower mass flows, higher current and higher magnetic fields, an increased amount of incoherent signal appears, and there is less evidence of the rotational fluctuation.

Spectroscopic Measurements of Velocities and Plasma Constituents

Preliminary spectroscopic measurements to determine plasma constituents and ion and neutral velocities have been made. These measurements were made using a similar accelerator, however, with a smaller vacuum chamber at pressures around 2×10^{-2} torr. The accelerator was operated at arc currents of 300 amps, magnetic fields of 2500 to 6000 gauss, and mass flow rates around 0.002 to 0.008 g/sec in ammonia. The low mass flow was needed in order to maintain sufficiently low tank pressures to minimize entrainment.

Side-on observations at 10 cm downstream from the outer face of the anode, using a 1.5-meter ARL Czerny-Turner spectrograph, indicate that N II exists only in the center of the jet while neutral hydrogen exists both in the center and in the outer regions. Molecular bands, including N_2 bands, appear to exist only in the outer regions of the exhaust, which could be due to recombination in the cooler area. The accelerator was also operated with a mixture of hydrogen and nitrogen as the propellant and the spectrograms obtained from the resulting plasma were similar to those obtained from ammonia plasmas at the same distance downstream.

Some ion and neutral axial velocity measurements have been made spectroscopically making use of the Doppler shifts of the emitted spectral lines. These measurements were made with an observation angle of 45° with respect to the accelerator axis in order to avoid looking in between the electrodes. These measurements are also necessary if the velocity gradients are sufficiently large to require an Abel inversion of the velocity distribution. The velocity component in this direction could then be used to obtain the value of the component along the accelerator axis. A hollow-cathode ion reference source, as well as the spectrum obtained from observations perpendicular to the axis of the plasma jet were used as standards for measuring plasma spectral line shifts. At present, spectral line shifts of nitrogen ions, looking especially at the 5005.14 Å N II line, have indicated axial velocities from 10,000 to 20,000 meters/sec depending on mass flow and magnetic field. Preliminary measurements of the 4861.33 Å H_β line shifts indicate neutral velocities about half that of the ion velocities. Both nitrogen ion and hydrogen neutral velocities increase with increasing magnetic field and decreasing mass flow. Further Doppler shift measurements will be performed at higher mass flows in the larger vacuum facility.

Measurements of Potentials and Electric Fields

Measurements of fluctuating and steady components of electric field and potentials were made along a diameter of the arc exhaust, by traversing a pair of probes mounted on a swinging arm, long enough so that field measurements were essentially in the radial direction. Motion pictures were taken of the oscilloscope face at 60 frames per second, with a rapid traverse, in order to take several data points during each probe sweep while avoiding probe heating. The oscilloscope trigger was fired once at each shutter opening. Two sets of measurements were made, one at 6.25 cm and one at 1.25 cm from the arc anode, with 0.3-mm and 0.2-mm separation between the probes, respectively. For the steady field and potential measurements, the possibility of spurious voltages produced by the presence of fluctuations was eliminated by inserting a large value of resistance in each probe circuit close to the probe, so that the probe presented a high impedance to the plasma. This allowed the probe to avoid a rectification effect that would result from the presence of cable capacity.(4)

Table 1 lists peak values of electric field taken from the field distribution curves, as well as arc voltage, for various values of magnetic field, arc current, and mass flow, for argon and ammonia. It can be seen that the peak value increases with both magnetic field and current. Also, at the higher magnetic field, an increased arc current produces a larger peak value even when the overall arc voltage remains constant or decreases. This agrees with the observation that the electric field is redistributed under these conditions, and concentrates at the outside edge of the plasma jet, which is an extension of the anode region along a magnetic flux line.

Figure 5 shows the electric field distribution obtained at 1.25 cm from the anode in ammonia at 6000 gauss and 300 amperes with a mass flow of 0.01 g/sec. The field is symmetrically distributed and reaches a peak value of 50 volts per centimeter. This region of maximum field may be interpreted as being on the edge of the plasma jet, and is probably identifiable with a narrow bright region which is often visible there. The secondary peaks are outside the plasma jet and are probably associated with a sharp-edged metal ring adjacent to the arc which is part of the structure of the tank and which is near the probes at their outside position.

Another operating condition is shown in figure 6, at a higher current (500 amperes) and lower mass flow (0.006 g/sec) and same magnetic field (6000 gauss). The electric field is redistributed and reaches higher values toward the outside of the plasma jet. The jet is, however, asymmetric at this operating condition.

Measurements at 6.25 cm showed that the structure at 1.25 cm was still maintained at that distance. The field distributions for argon were generally more complex than for ammonia, and the amplitude generally lower, in relation to the total arc drop.

Figure 7 is a sample of potential fluctuation measurements taken with two probes with 2-millimeter separation. In figure 7(a) the output of the two probes is recorded separately; in figure 7(b) the difference of potential is shown. These measurements were taken in ammonia, for mass flow of 0.01 g/sec, magnetic field of 3000 gauss, and current of 300 amperes, at a radius of 1 cm, at 1.25-cm axial distance from the anode. The coherent frequency in figure 7(a) is about 250 kc, and the amplitude about 15 volts peak to peak for an arc voltage of 70 volts and a drop in floating potential of 24 volts across the jet at this axial distance. These floating potentials need large corrections in view of the high electron temperatures found in the MPD arc. The difference record, figure 7(b), taken at the same operating conditions as figure 7(a), but during another test, shows that there are both coherent and incoherent components of the potential at this distance. This is characteristic of records taken at other conditions. The motion-picture sequences indicate that at the higher magnetic fields and currents, the oscillations become more intense toward the outside of the arc where the average measured electric fields also have high values. It was found also that pure nitrogen and hydrogen showed very large fluctuations as compared with ammonia and mixtures of N_2 and H_2. Preliminary measurements of oscillations due to rotating disturbances in argon and their relation to those in the linear Hall accelerator were discussed in reference 5.

Thrust Measurements for Various Propellants

Thrust measurements have been made in hydrogen, deuterium, nitrogen, ammonia, and mixtures of nitrogen and hydrogen using a thrust disk as described in reference 5. For these tests the maximum gas flows were 1000 cc/min. This corresponds to 1.5 mg/sec for hydrogen, 3 mg/sec for deuterium, 21 mg/sec for nitrogen, and 13 mg/sec for ammonia. The number of atoms flowing per second multiplied by the electronic charge defines a current J_{cr}. At 1000 cc/min this current is 140 amps for H_2, N_2, and D_2 and 280 amps for NH_3. Thrust measurements were made at 100 to 500 amps; thus the arc was operated above and below the previously defined current. If a critical mass flow is defined as $\dot{m}_{cr} = (J_{cr}/e)m$, this is equivalent to operating above and below the critical mass flow. No remarkable change in operation was found in crossing this point. For operation in hydrogen and deuterium at 1000 cc/min, velocities based on thrust and mass flow are reasonable at 100 to 300 amps but for currents well above the critical current the thrust measurements indicate impossibly high velocities and efficiencies. The high thrust found for these operating conditions below the critical mass flow $\dot{m} < \dot{m}_{cr}$ is probably due to gas entrainment or electrode erosion (ref. 5). Velocities for the heavier gases (NH_3 and N_2) based on thrust over mass flow were reasonable for all operating conditions, including those above and below the critical mass flow. However, it should be pointed out that the effect of extraneous thrust on velocity measurements based on thrust and mass flow is much higher for lighter gases, such as H_2 and D_2, than for NH_3 and N_2. Thus, there still exists the possibility of some entrainment or electrode erosion for operation below the critical mass flow in the heavier gases. This will be checked spectroscopically while Doppler shift measurements are being made in the large vacuum facility. The velocities found for N_2 and NH_3 based on thrust and mass flow are of the order of the velocities found using ion density fluctuations and using Doppler shift in the smaller vacuum facility.

In general, an increase of thrust is found for increase in current or for an increase in volume flow for a particular gas. An increase in thrust is also found for an increase in mass flow, made by substituting deuterium for hydrogen, at a particular volume flow. No regular increase in thrust is found with magnetic field at the two field strengths of 3000 and 6000 gauss used here.

Discussion of Results

The time-of-flight velocity measurements making use of correlations between propagating fluctuations yield considerably higher values for light and potential fluctuations than for ion density fluctuations in the axial direction. The latter velocity values are in better agreement with those obtained from thrust and mass flow. It is possible that the propagation of light and potential fluctuations may be related to the propagation of disturbances of the electron flow along the magnetic field lines. Further studies are necessary to distinguish between velocities along the axis of the plasma jet and the axial velocities at anode distance where the electron currents are reversed. Finally, it should be noted that usefulness for velocity measurements of the propagation of ion density fluctuations is enhanced for the case where the plasma velocity is much higher than the relative phase velocity. This condition is satisfied when dealing with ion sound waves. A stationary probe would observe a combination of $u + a$ and $u - a$ where u is the flow velocity and a the relative velocity of propagation.

The similar time-of-flight measurement for azimuthally moving perturbations is obtained from two 90° azimuthally displaced probes. At axial distances of 1.25 and 6.75 cm from the anode the rotation is still apparent and disappears at distances of about 12 cm. The problem as to whether or not the velocity of the rotating disturbance represents a true fluid rotation must be studied further. In this connection it should be noted that there exists a basic difference between the axial and the rotating disturbance. The axial ion density fluctuation appears to be convected with the moving plasma. The situation is, however, not necessarily the same for the rotating disturbance (which at comparatively high B_Z develops into one or several spokes) since it can be driven directly by $j_r B_Z$ and could drag some of the plasma with it. The problem whether the bulk plasma is put into rotation by the $j_r B_Z$ force in the disturbance or outside it depends on the relative order of magnitudes of oscillating and steady values of electric fields in the laboratory frame. Measurements indicate that the oscillating potentials are somewhat smaller than the steady potentials. On the whole, the velocities of rotating disturbances can be regarded as an upper limit of plasma rotational velocity. Doppler shift measurements will be performed of the azimuthal velocities of ions and neutrals. For example, for rotational frequencies of 250 kc observed for some operating conditions, the azimuthal velocities $v_\theta = 2\pi rf$ would correspond to 1.5×10^4 m/sec.

The measurements of steady electric fields indicate a redistribution with increasing magnetic field and current towards the edge of the plasma jet emerging from the anode region. Such redistribution has been also observed with increased magnetic field for PIG discharges operating at low pressures. The arguments used are essentially that for very small Larmor radii and large values of $\omega_e \tau_e$, the electrons cannot gain sufficient energy for ionization within the electrode region and thus large fields must exist near the anode. The argument appears to become stronger if large currents are to be maintained across comparatively high magnetic fields. A similar argument can be used for the necessity of oscillating electric fields even in the presence of medium magnetic fields; the oscillating electric fields permit the electrons to gain more energy for ionization than they would under the restriction of small Larmor radius (or in the presence of collisions a large value of $\omega\tau$). Concerning the distribution of steady voltages on which the steady values of the electric field are based, it is important to emphasize that they represent floating potentials and need to be corrected for the high electron temperatures; details are given in the companion paper by Brooks, et al.

In order to determine the effect of oscillations on the mechanism of acceleration or containment measurements have to be made of the enhanced current across the magnetic field due to these oscillations. Such measurements of oscillations due to rotating disturbances of spokes have been performed previously in the Linear Hall Accelerator and the MPD arc and more recently in the device discussed in the paper by Brooks, et al.

It is of special interest to note that the amplitude of the oscillations is higher when nitrogen or hydrogen alone are used as propellants in contrast to mixtures even when the arc voltage does not undergo a corresponding reduction. The problem of whether this reduction in noise is connected with an increase in thrust or efficiency is one of great interest and is being studied in greater detail; especially, its relation to the percentage neutrals in the jet and theoretical models of critical mass flow is being evaluated.

The spectroscopic measurements of velocity by Doppler shift made in a small vacuum chamber indicate that at the very low mass flows of 0.002 to 0.008 g/sec in ammonia the neutral hydrogen is not efficiently accelerated. The neutral hydrogen has a lower velocity than the ionized nitrogen as well as the ionized hydrogen which should have higher velocity, but cannot be observed spectroscopically; this finding agrees with critical mass-flow models where acceleration of neutrals is not included. Further Doppler shift measurements will be performed at higher mass flows in the larger vacuum facility, where the other measurements reported in this paper were performed. These measurements should give more complete insight into the utilization of neutrals in the acceleration process and the validity of critical mass-flow models at higher mass flows.

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Table 1 .- Variation of maximum electric field and arc voltage with B and I, at 1.25 cm distance from anode.

ARGON

B (Gauss)	I (Amperes)	$\dot{m}$ .02 gr/sec Arc Volts	$\dot{m}$ .02 gr/sec Max V/cm	$\dot{m}$ .01 gr/sec Arc Volts	$\dot{m}$ .01 gr/sec Max V/cm
3000	300	45	10	50	25
3000	500	50	15	65	23
6000	300	80	28	80	59
6000	500	70	59	75	64

AMMONIA

B (Gauss)	I (Amperes)	$\dot{m}$ .01 gr/sec Arc Volts	$\dot{m}$ .01 gr/sec Max V/cm	$\dot{m}$ .006 gr/sec Arc Volts	$\dot{m}$ .006 gr/sec Max V/cm
3000	300	70	25	75	27
3000	500	70	27	75	44
6000	300	90	60	100	73
6000	500	75	70	75	75

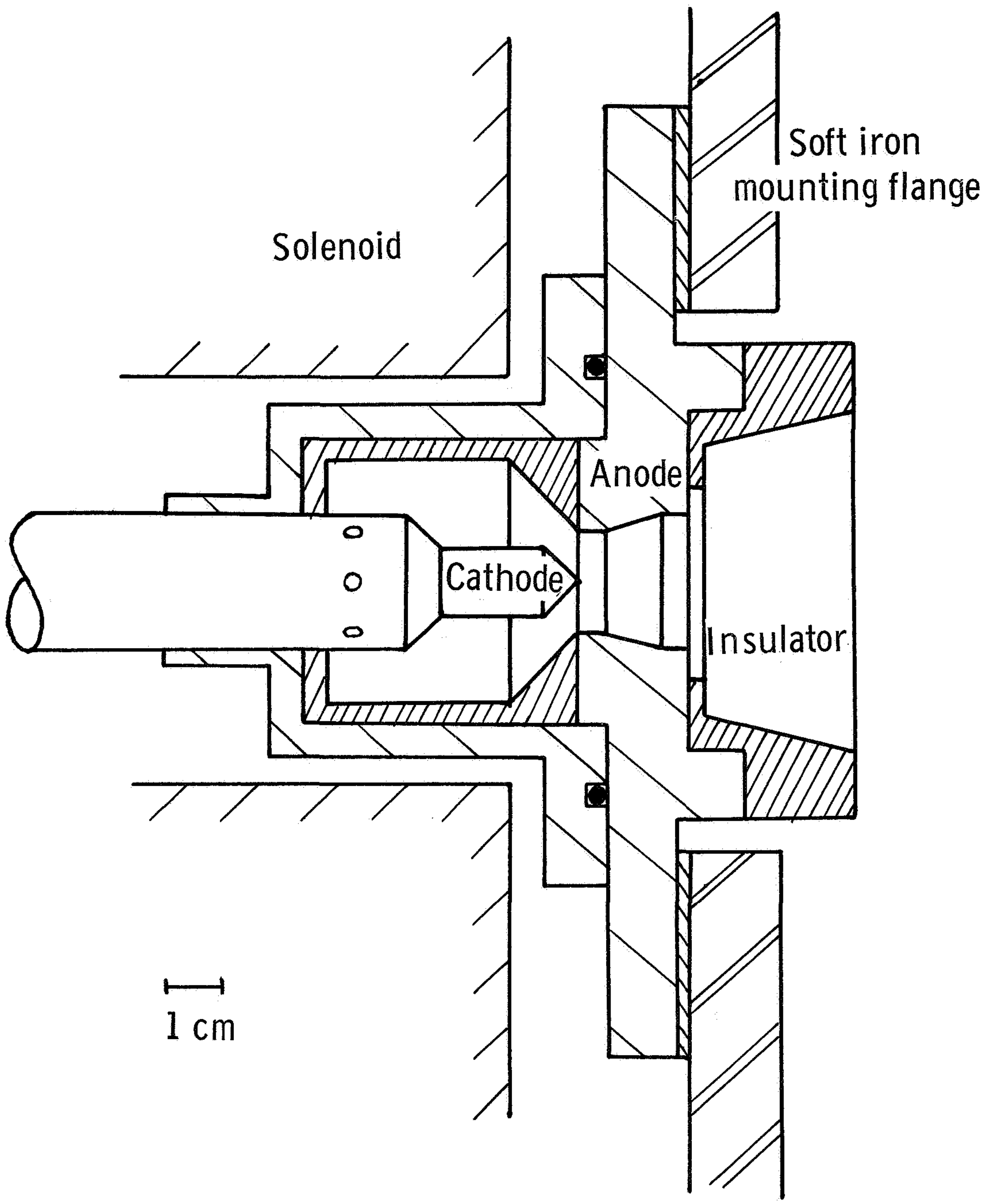


Figure 1.- Schematic of accelerator.

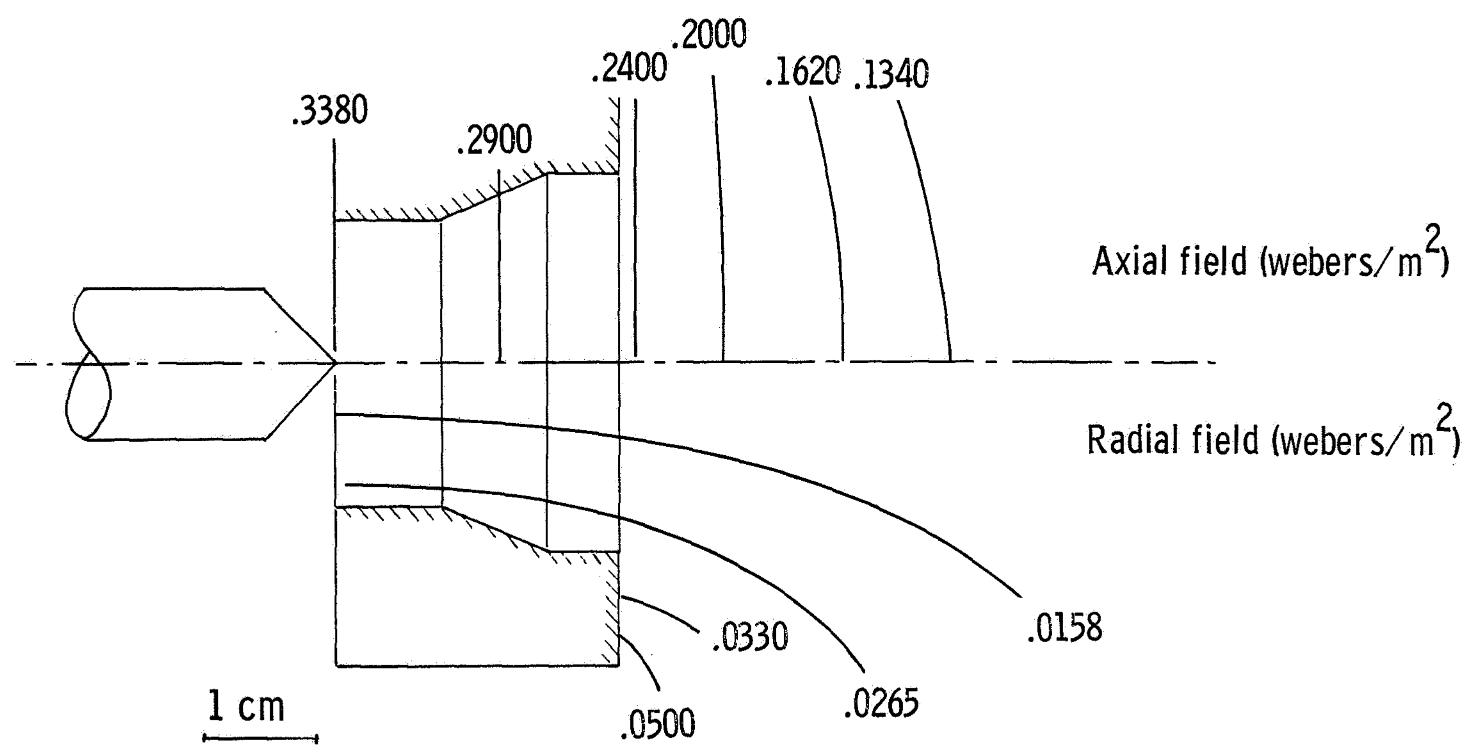


Figure 2.- Magnetic field distribution.

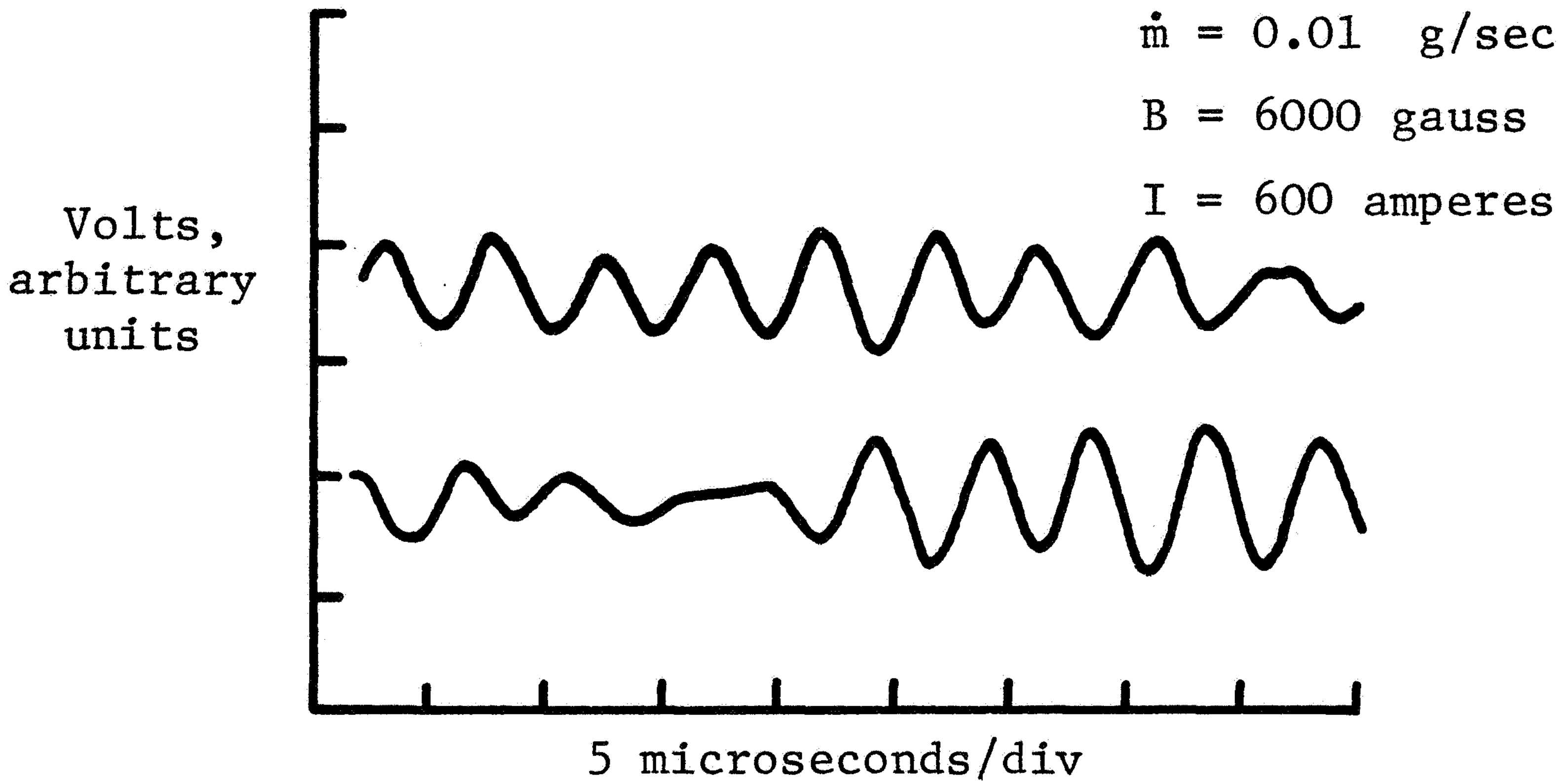


Figure 3.- Light perturbation measurement of velocity in ammonia. Probe separation 20 cm.

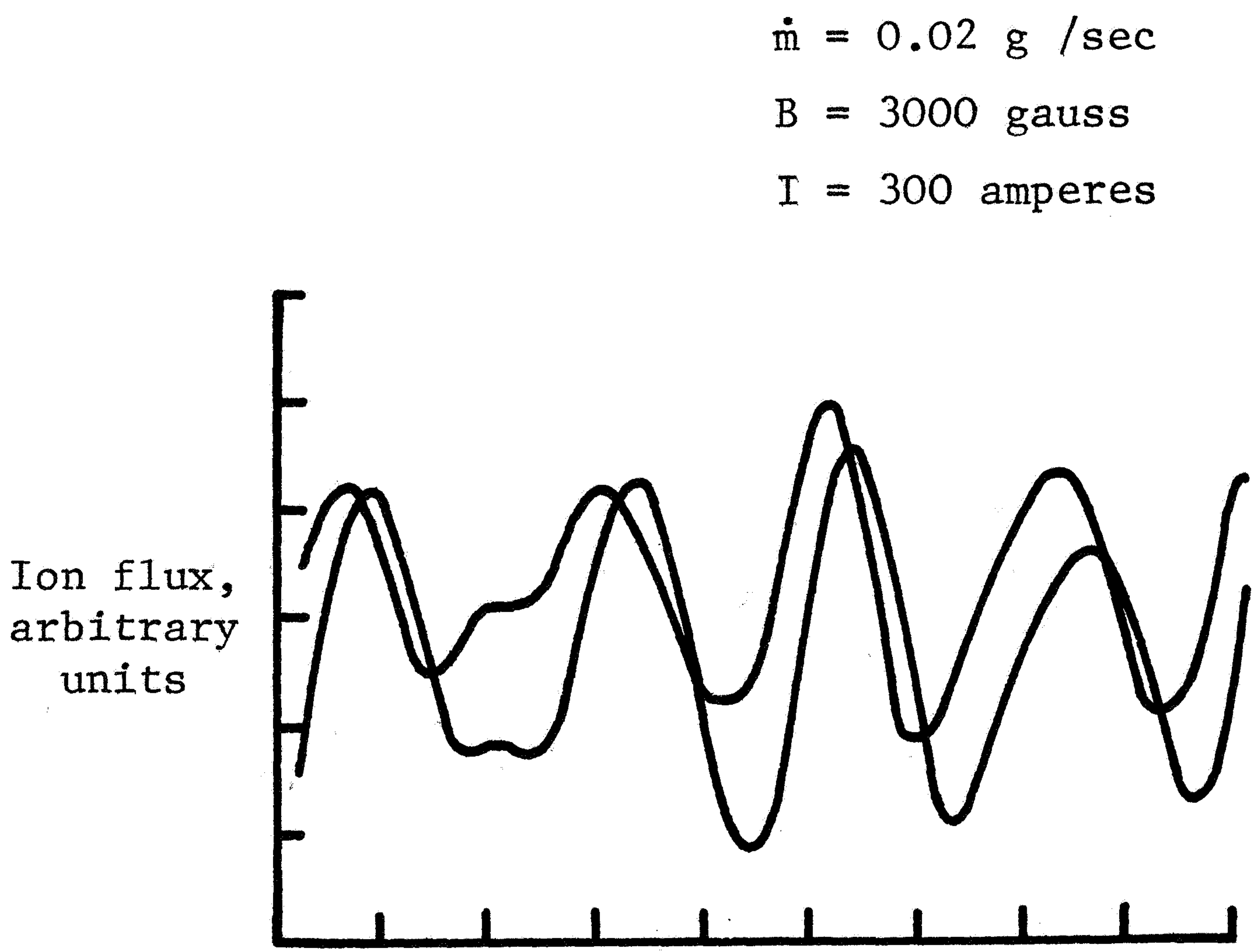


Figure 4.- Ion flux perturbation measurement of velocity in argon. Probe separation 2 cm.

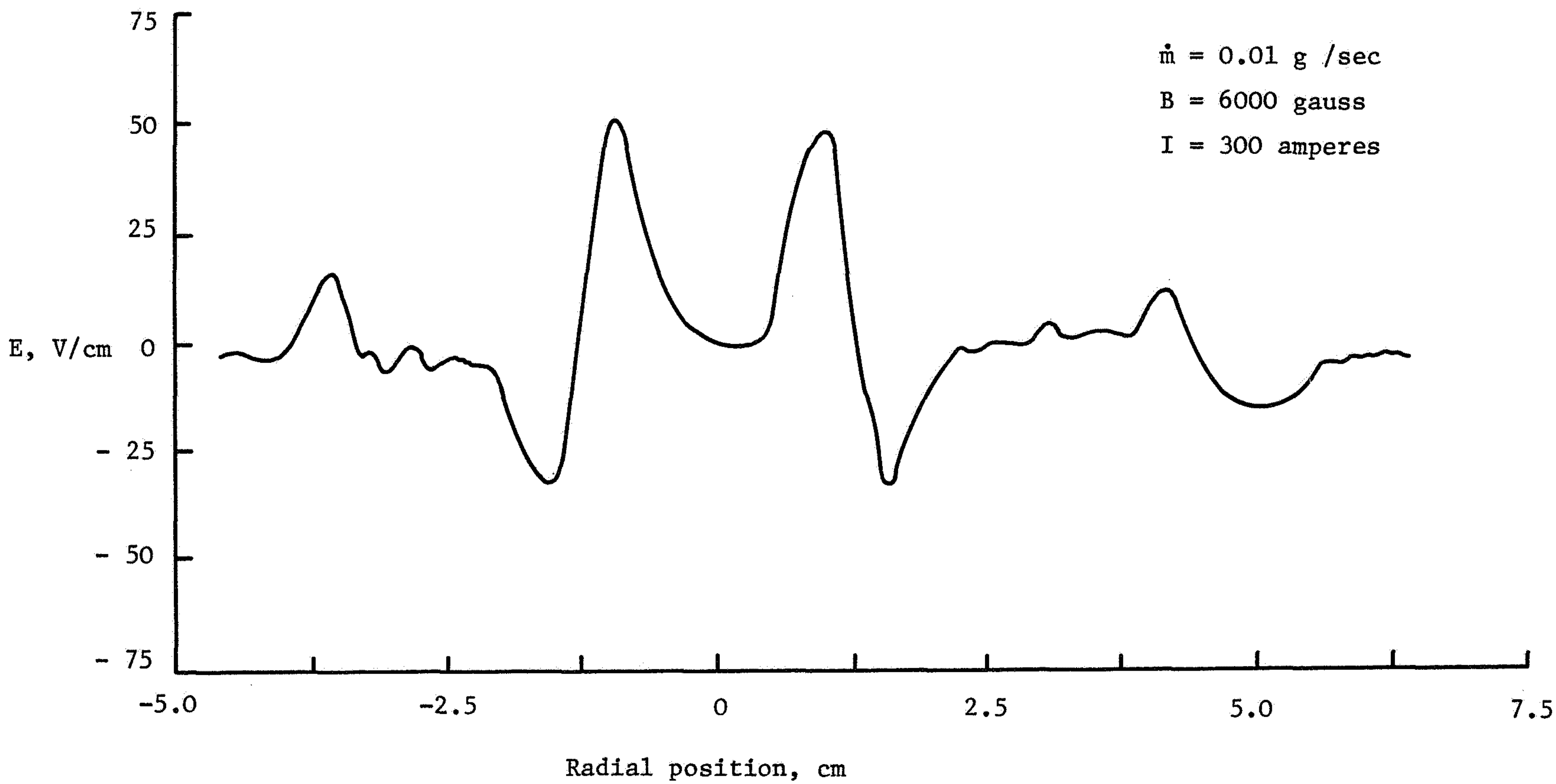


Figure 5.- Variations of radial electric field with radial position, 1.25 cm from arc, symmetric operation.

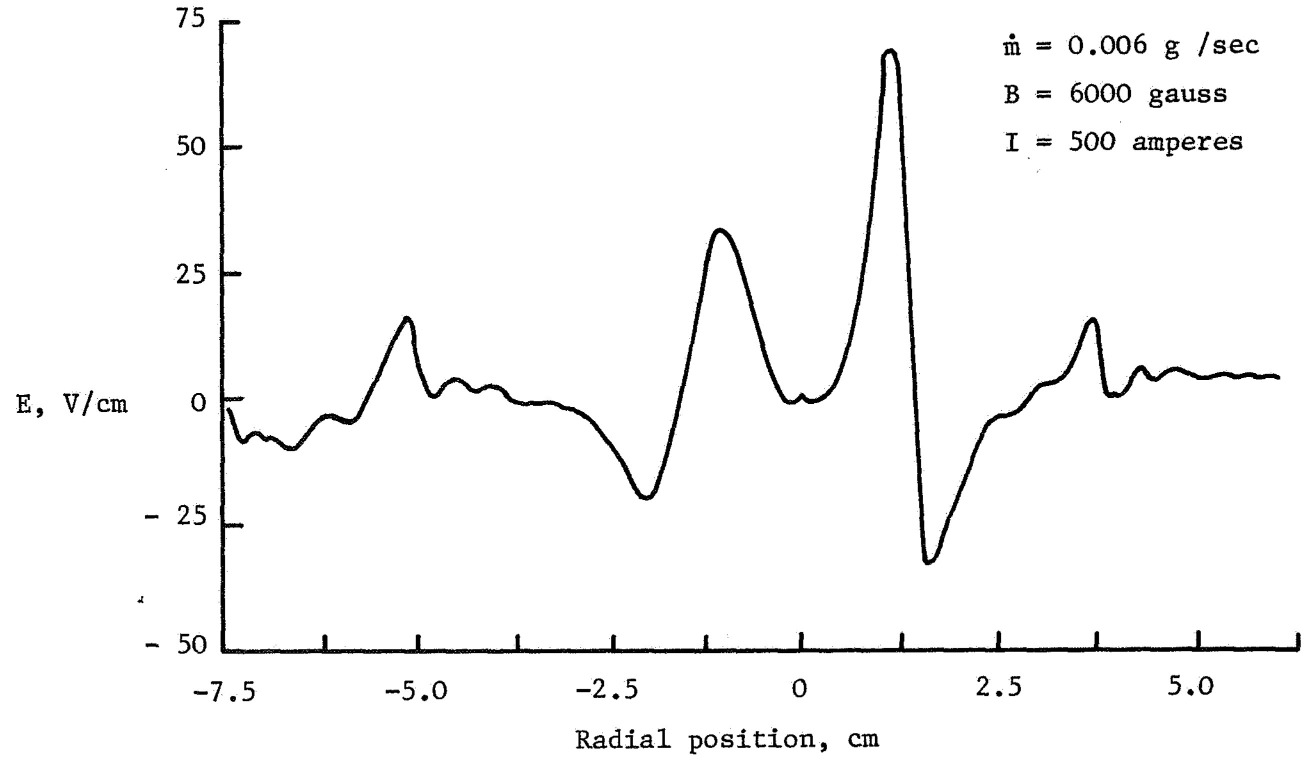
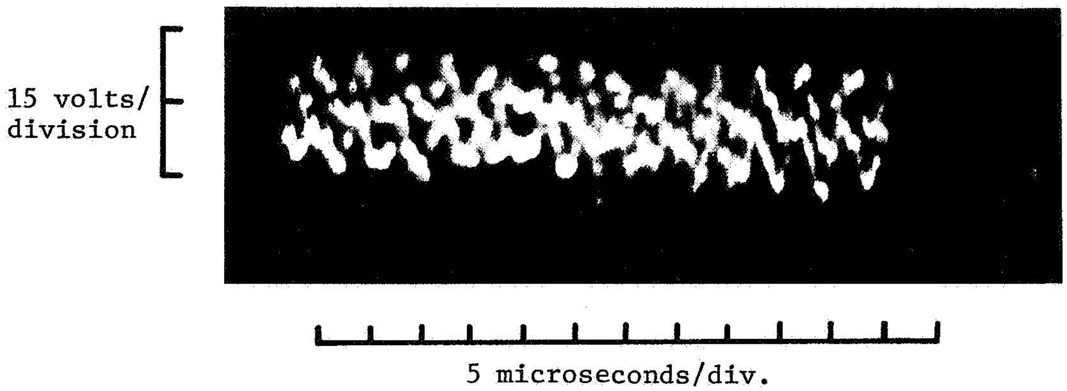
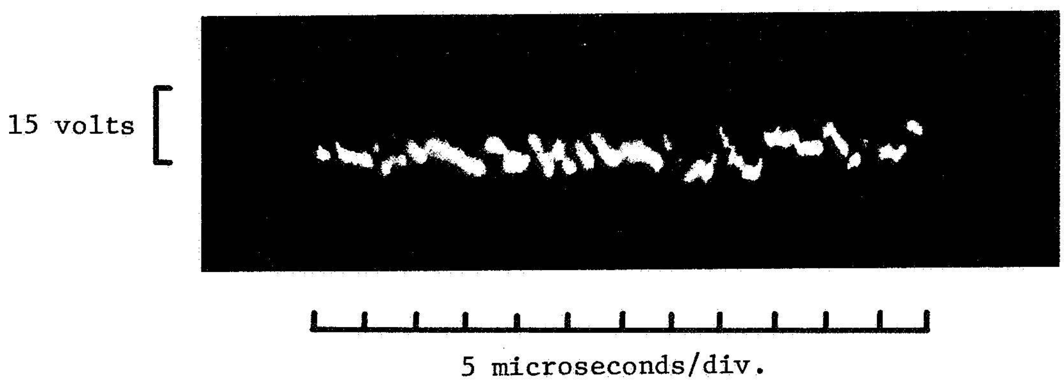


Figure 6.- Variation of radial electric field with radial position, 1.25 cm from arc, unsymmetric operation.



(a) Potential fluctuations. B = 3000 gauss, I = 300 amperes, mass flow 0.01 g /sec.



(b) Potential difference fluctuations. B = 3000 gauss, I = 300 amperes, mass flow 0.01 g /sec.

Figure 7.- Fluctuation measurements

NASA-Langley, 1967