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Scientific Report No. 354

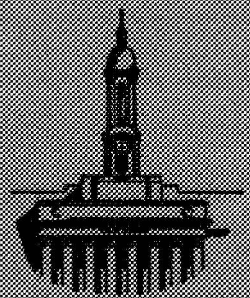
INVESTIGATIONS OF LOW FREQUENCY OSCILLATIONS IN A SPHERICAL, COLD CATHODE DISCHARGE IN THE PRESENCE OF A DIPOLAR MAGNETIC FIELD

by

P. E. Schmidt and R. G. Quinn

April 20, 1970

IONOSPHERE RESEARCH LABORATORY



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Ionospheric Research

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Scientific Report

on

"Investigations of Low Frequency Oscillations in a Spherical, Cold Cathode Discharge in the Presence of a Dipolar Magnetic Field"

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ABSTRACT

Coherent very low frequency oscillations have been experimentally investigated by means of probes. Utilizing a single probe, it is found that the maximum of the oscillations is located in the negative glow of the discharge. By means of a two-probe technique it is found that there exists a $2m\pi$ phase shift in the angular direction with $m = 0$ for low discharge currents and $m = 1$ for high discharge currents. No radial phase shift is observed under any discharge and pressure conditions.

A simple theoretical model is developed with explains much of the experimental data. Theoretical and experimental studies are suggested which could lead to a more thorough understanding of the phenomena.

I. INTRODUCTION

Coherent very low frequency oscillations are found in a spherical magnetized cold cathode DC discharge. (Schmidt and Quinn, 1969) The previous study examines in detail the two terminal characteristics of the device. The oscillations which arise have been found to vary with the neutral gas species and pressure, the voltage and current in the discharge and the size of the cathode.

This study is the continuation of the above mentioned investigation. Probes are used as diagnostic tools for determining the location of the maximum of the oscillations and the wavelength respectively in the radial and angular directions. A simple theoretical model whose basic assumptions are verified by experimental evidence is then developed. It is shown that this model predicts much of the experimental results. Finally, a number of suggestions for further experimental and theoretical studies are discussed.

II. INVESTIGATION OF LOW FREQUENCY OSCILLATIONS UTILIZING PROBES

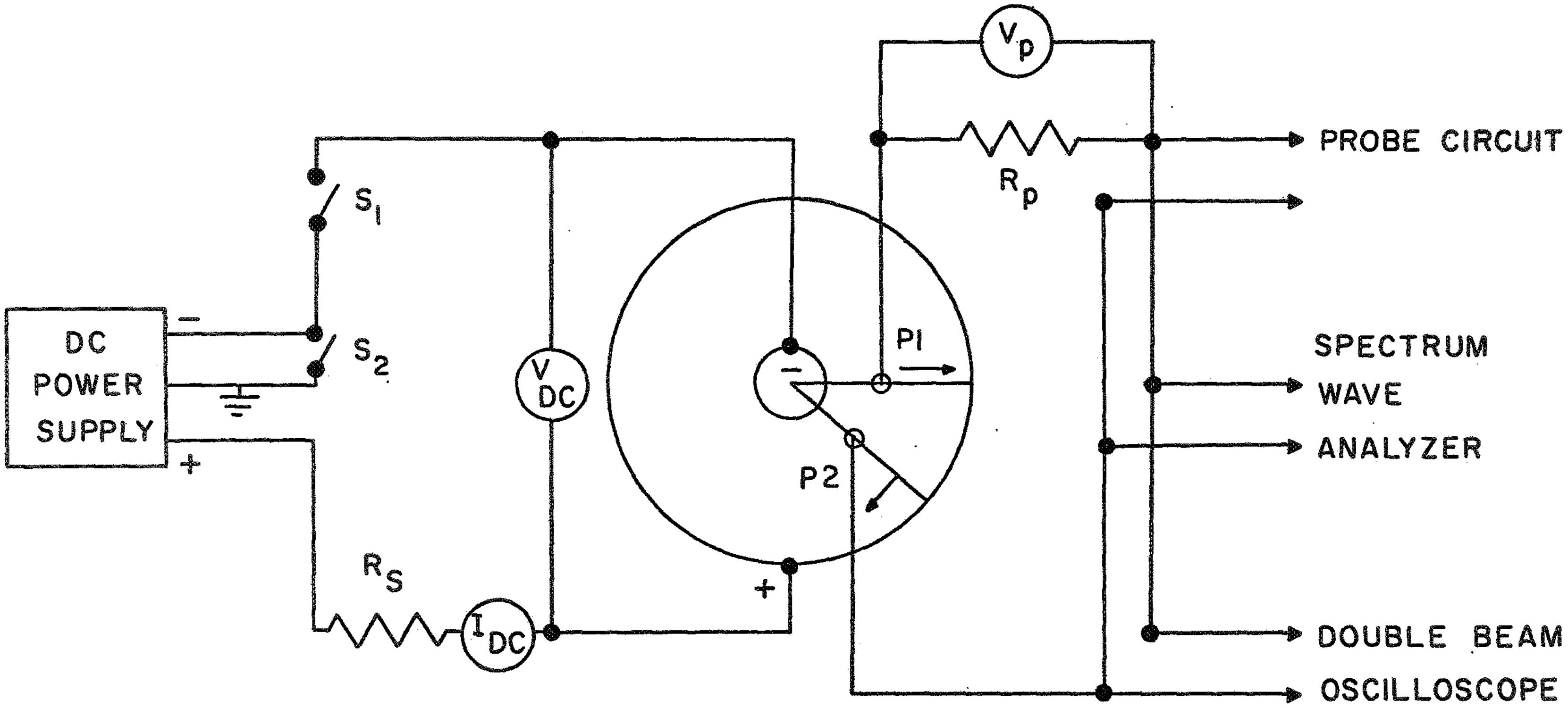
II. 1 APPARATUS AND MEASURING PROCEDURES

II. 1. 1 Description of Apparatus

The schematic of the experimental apparatus with probes is shown in Figure II. 1. 1. The vacuum system and the discharge circuit are identical with the apparatus discussed in a previous report.(Schmidt and Quinn, 1969) Therefore, we will focus our attention on the modifications which are necessary to incorporate the probes.

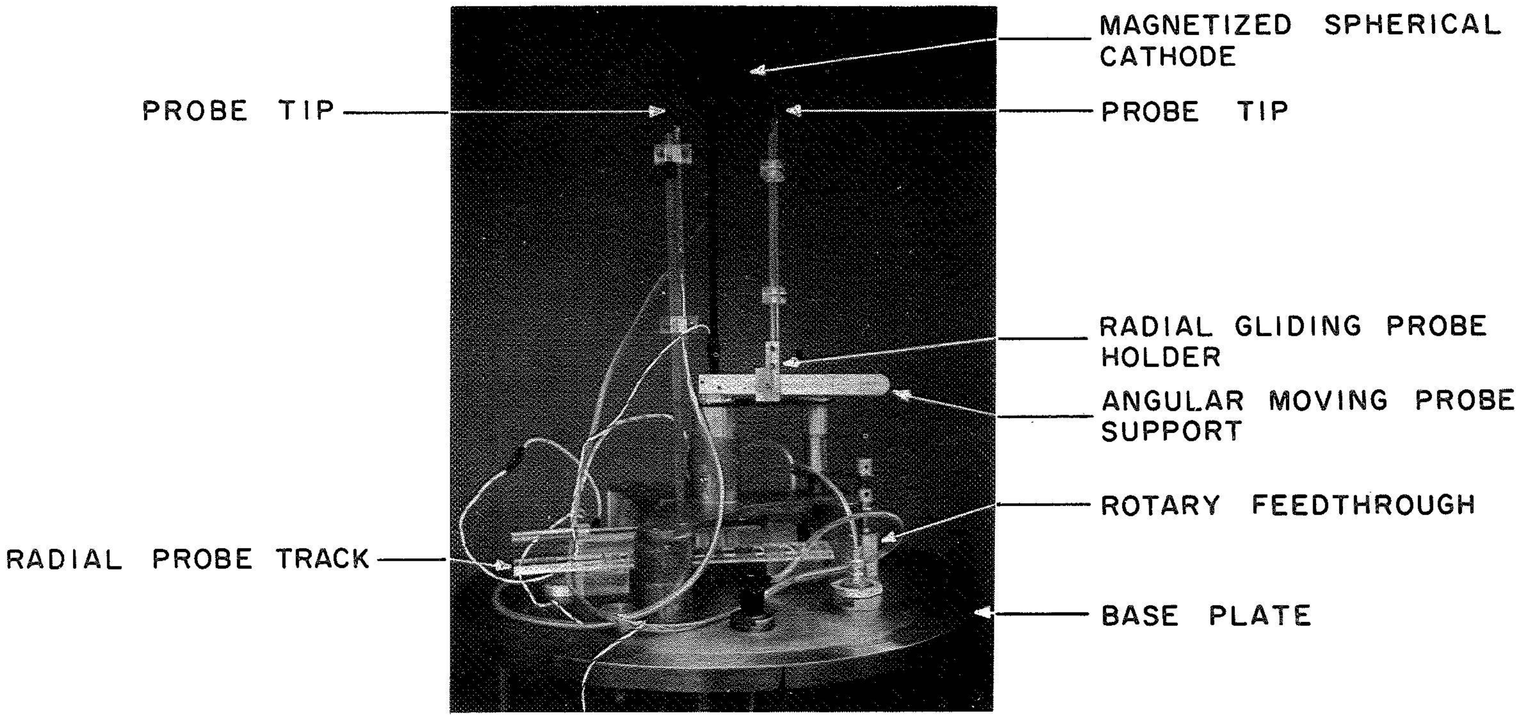
Before describing the total probe system, the following items will be defined. A single probe is an exposed piece of tungsten wire immersed in the plasma to detect oscillations and determine the location of their maximum amplitude. A two-probe system is composed of two single probes which can be displaced with respect to each other. It is by means of the two-probe system that one can detect and investigate the wavelength of the plasma oscillations.

In Figure II. 1. 2 the total probe system is shown. It consists of two main parts. The first part is composed of a slide track upon which a probe carriage with probe holder moves radially. The drive mechanism is a long worm screw passing through a threaded part of the probe carriage. The screw has at one end a gear which is part of a miter gear. The mating gear is fixed to the shaft of a rotary feedthrough. This part of the probe system is used for the single probe and double probe measurements. The second part consists of an angular moving probe support with a radially displaceable probe-



Schematic of the Experimental Apparatus with Probes

FIGURE III. 1. 1



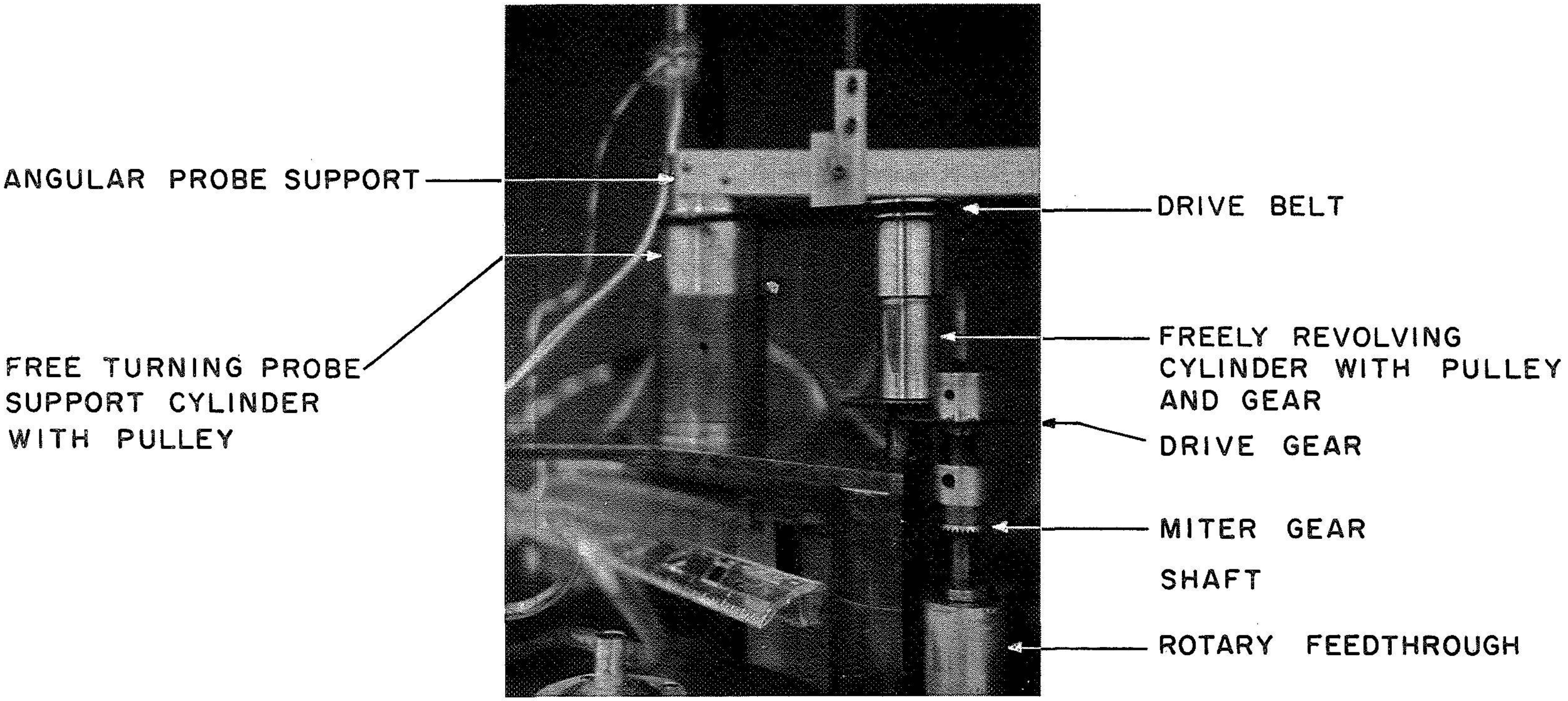
Total Probe System

FIGURE II. 1. 2

holder. The probe arm is fixed to a cylindrical piece of copper, coaxially mounted to the sphere support. The upper part of the cylindrical piece is a pulley in which a drive belt fits. A second pulley is part of a freely revolving cylinder driven at its end by a drivegear. The drivegear is fixed to the shaft of the rotary feedthrough. This part of the probe system in conjunction with the first part is used for the measurement of the wavelength of the plasma oscillations in the angular direction. A close view of the drive mechanism is shown in Figure III. 1. 3. As one can see, the radial and angular motions are commanded by the same rotary feedthrough. Nevertheless, both motions can be performed independently.

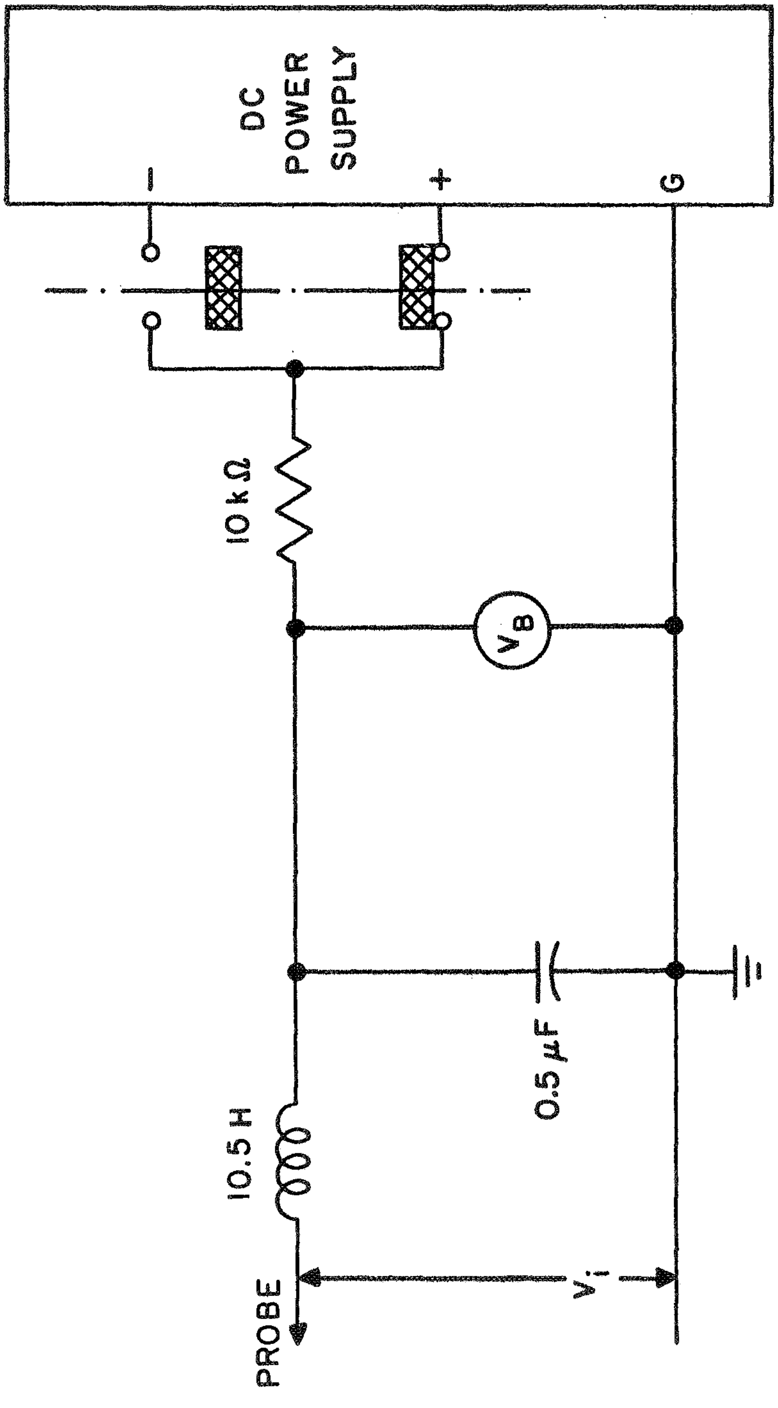
The probes are made of tungsten wire (0. 25 mm in diameter) coated with glass except at the tip. The length of the exposed tip is not critical for the purpose of detecting the plasma oscillations or determining the wavelength of the oscillations.

The probes can be connected to a biasing circuit which is shown in Figure III. 1. 4. In Figure III. 1. 5 the experimentally determined attenuation versus frequency plot is given. It can be seen that, at low frequencies, the waveform of the plasma oscillations is distorted when the probe is connected to the biasing circuit. The voltmeter V_B gives the bias voltage, while the current through the probe is measured by means of the measurement of the voltage V_p over the 1 kOhm resistor, R_p, as shown in Figure III. 1. 1.



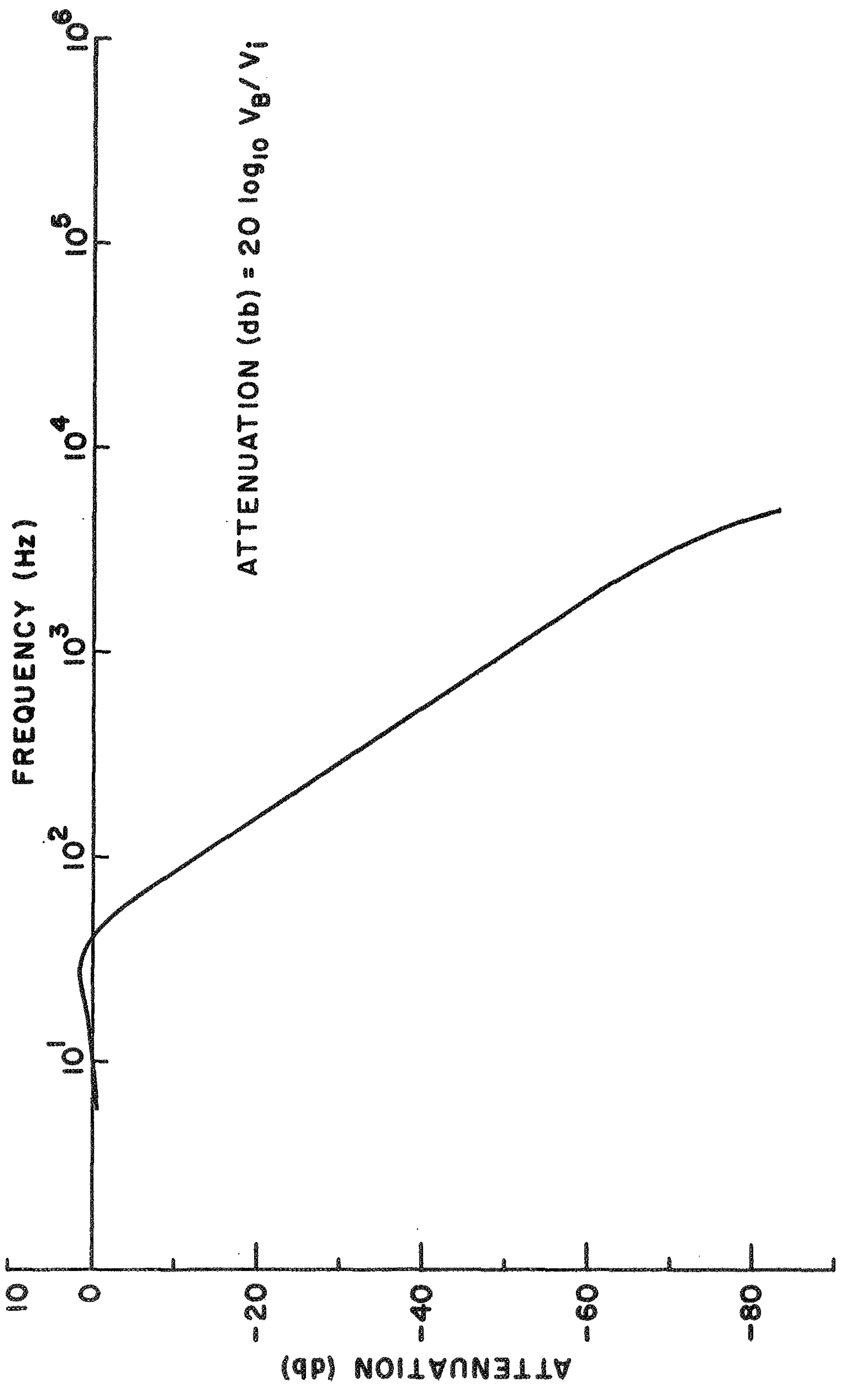
Probe Drive Mechanism

FIGURE II. 1. 3



DC Biasing Probe Circuit

FIGURE II. 1. 4



Experimental Attenuation vs Frequency Plot for Probe Circuit

FIGURE II.1.5

II. 1. 2 Measuring Procedures

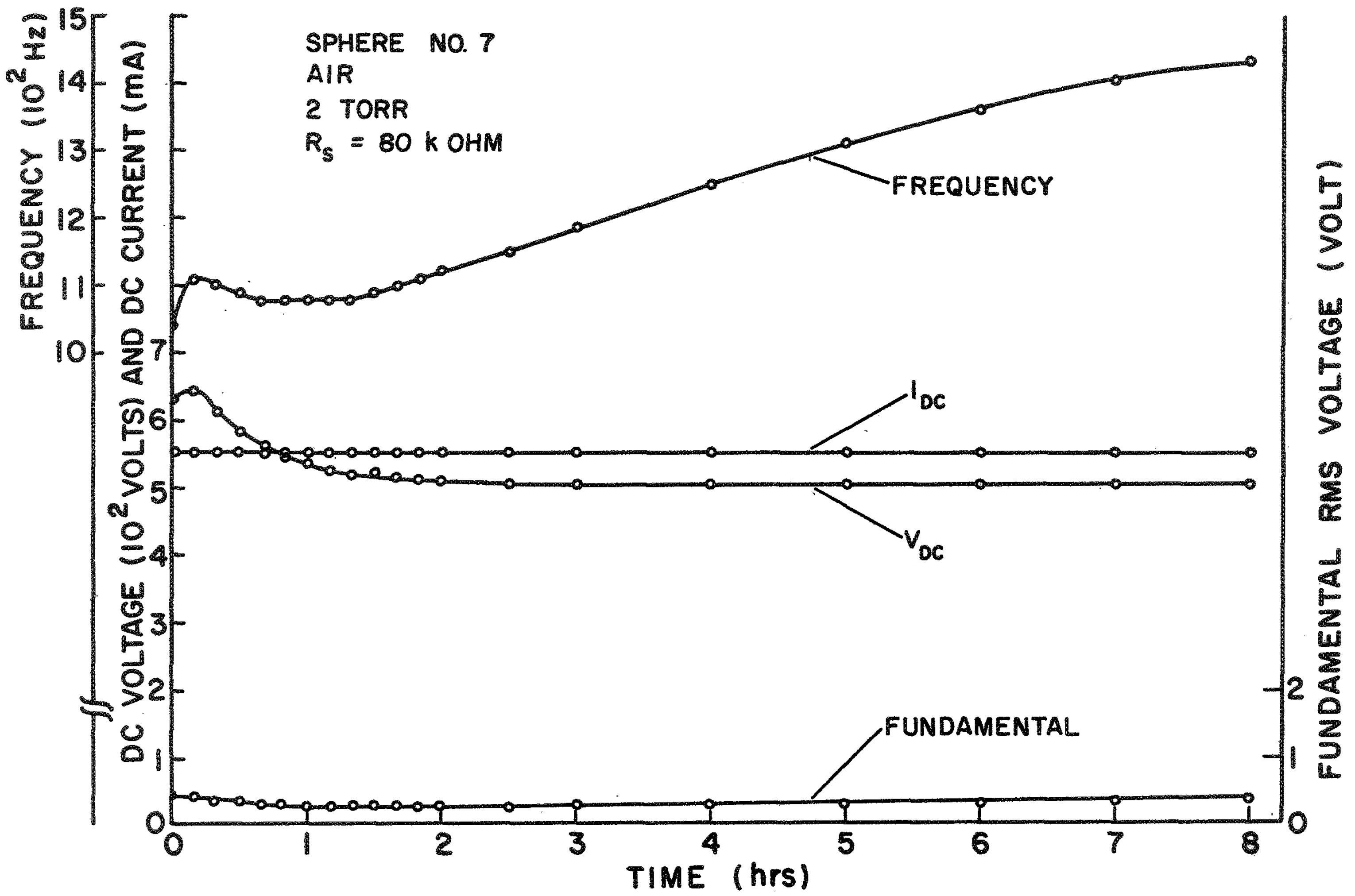
In all cases an antenna wound around the outside of the belljar was used as a monitoring device for observing the perturbing influence of the probe upon the plasma. For example, if one biases the probe too negatively or positively the character of the discharge changes completely. This change is noticed with the antenna. As pointed out by Schmidt and Quinn (1969), no change in frequency or in waveform is observed using a floating probe as a detecting device. For displaying the waveform or the spectrum, an oscilloscope or spectrum wave analyzer may be used.

II. 2 EXPERIMENTAL RESULTS

II. 2. 1 Frequency Shift in Time

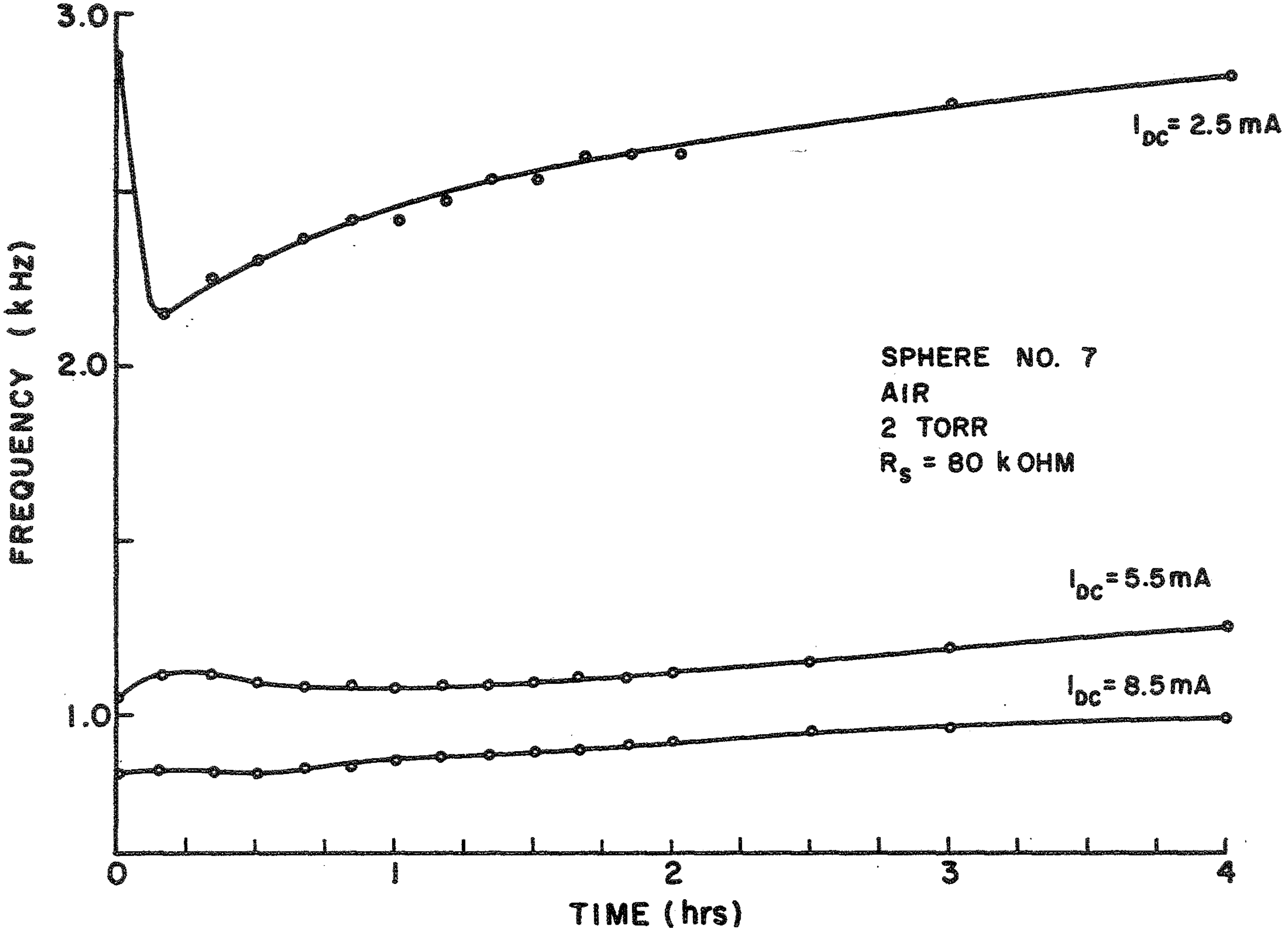
The stability of the frequency of oscillations as a function of time was examined during an eight hour experiment. The current was maintained constant during the experiment by adjusting the power supply when necessary. The measured variations of frequency, amplitude of the fundamental, and DC voltage are shown in Figure II. 2. 1.

It is seen that the amplitude is relatively constant in time but that the frequency is characterized by an initial "settling" period of approximately one hour during which it can either increase, decrease or remain constant. This "settling" period is followed by a period of gradually increasing frequency, the rate of which continuously decreases. The frequency of the plasma oscillations versus time for various values of DC discharge current is given in Figure II. 2. 2. We notice that again a decrease in DC current causes an increase in frequency, and an increase in frequency with time is observed for all DC current values. In Figure II. 2. 3, frequency versus time at 1 and 2 Torr is plotted for a DC discharge current of 5. 5 mA. It is noticed, as before, that the frequency increases with a decrease in pressure. Thus from these 2 graphs it is seen that the frequency shift in time does not alter the results obtained by Schmidt and Quinn (1969), as the characteristic time of these effects is long compared with the time of the experiment.



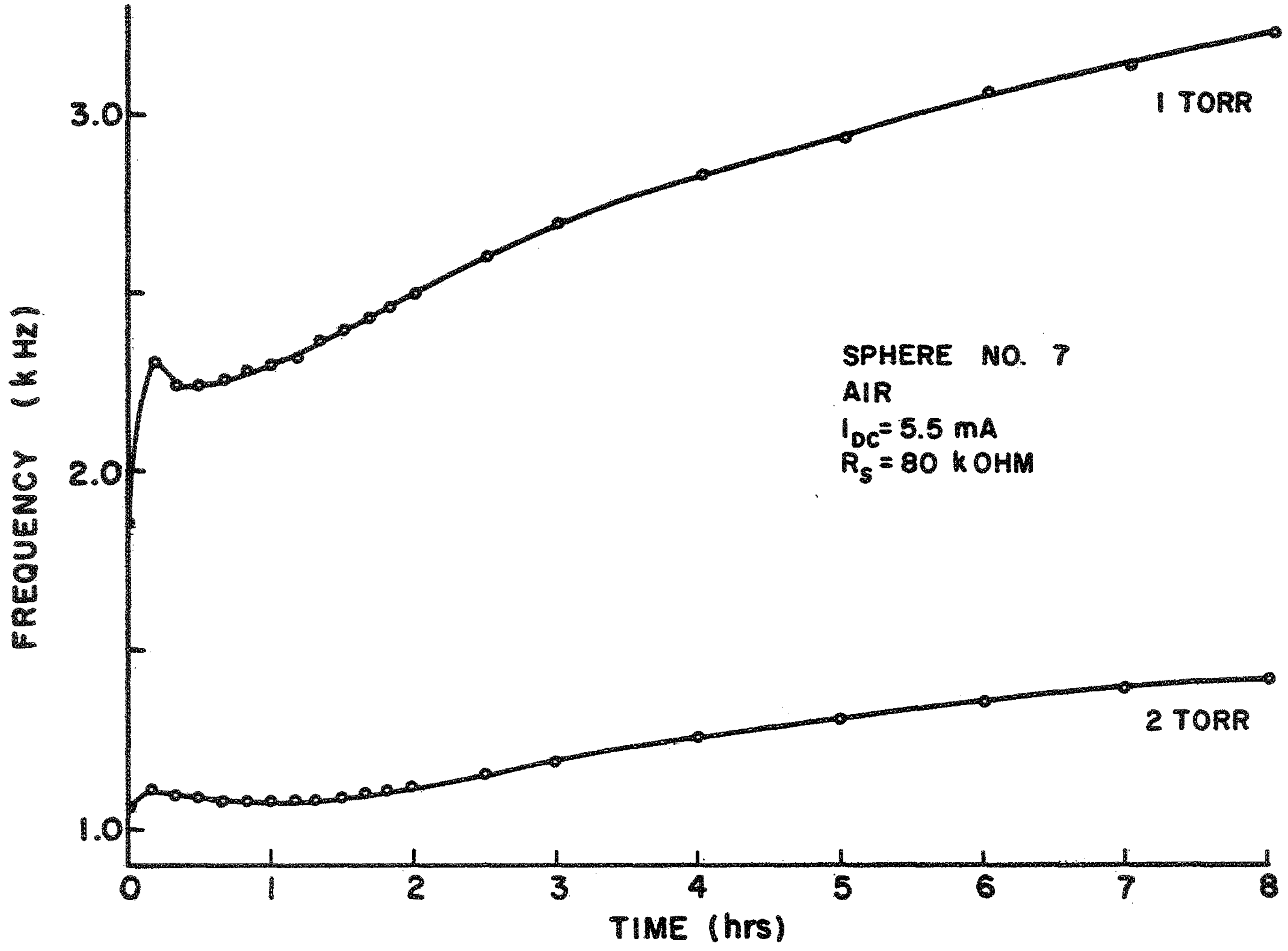
General Time Behavior

FIGURE II. 2. 1



Frequency vs Time for Various DC Currents

FIGURE II. 2. 2



Frequency vs Time at Different Pressures

FIGURE II. 2. 3

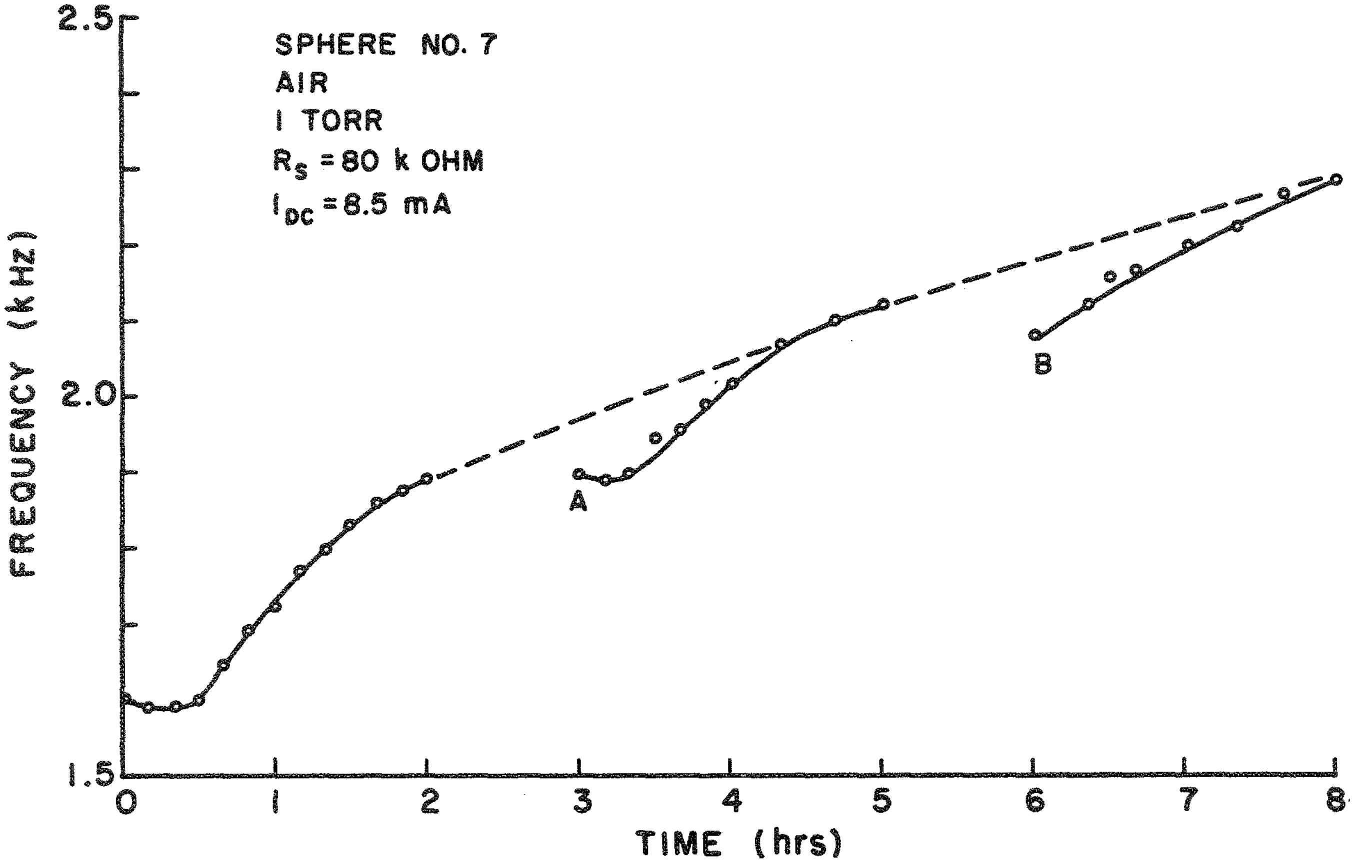
However, let us digress to examine the possible causes of this frequency shift.

When a constant current is maintained over an extended period, there is a slight increase in pressure. According to the results obtained by Schmidt and Quinn (1969), one would expect a corresponding decrease in frequency with time rather than the observed gradual increase. There are a number of possible factors which could cause this behavior, such as a vacuum leak, temperature rise of the cathode, local heating by the negative glow, change of magnetic field with temperature, or outgassing.

An influx of low molecular weight gas would cause an increase in frequency. A series of experiments to assess the magnitude of such changes was performed using pure helium as a simulated leak. The results indicate that the effect of vacuum leaks on the frequency is negligible for this experiment. In addition the magnetic field of the permanent magnet is not sensitive to temperature variations in the ranges under study.

A series of experiments were performed which demonstrate that the initial "settling" period is governed by the thermal effects of the cathode and cathode glow and that the range of slowly increasing frequency is governed by outgassing of the apparatus.

Figure II. 2. 4 presents the results obtained by maintaining the plasma for two hour intervals with one hour cooling periods in between. The dashed line is the curve for continuous operation.



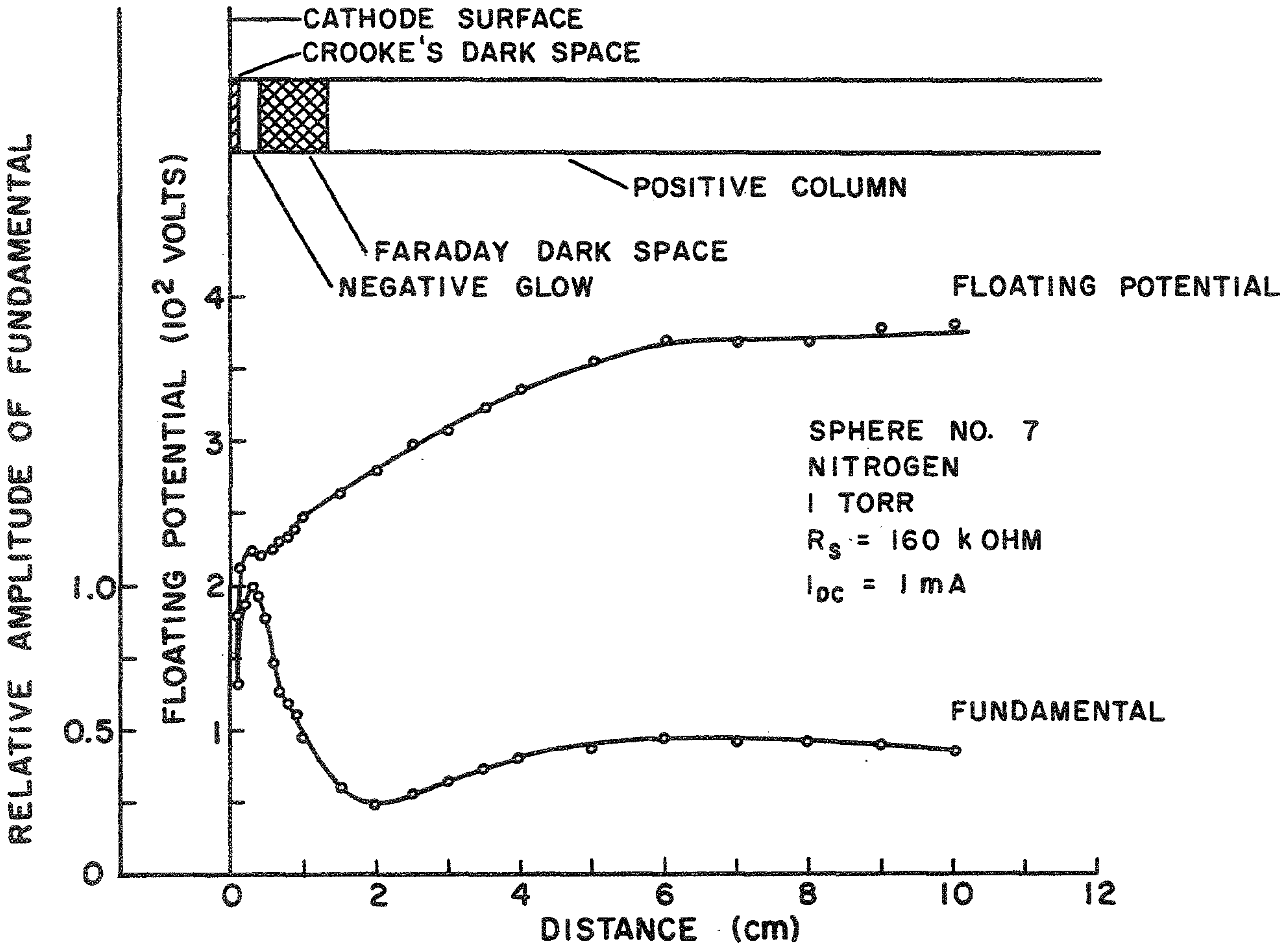
Frequency vs Time for Intermittent Operation

FIGURE II. 2. 4

It can be seen that after each cooling there is a transient period during which the frequency rises to the continuous operating value. However, the starting value of these transient portions is successively larger as time increases. It was separately verified that one could begin, say at point A, by merely filling the chamber to the desired pressure and waiting three hours or at point B by waiting six hours. This demonstrates that the starting point and final values are determined by outgassing, while the transient portion is due to thermal effects.

II. 2. 2 Location of the Noise Source

The data discussed here were obtained using the scanning instrumentation described in Section II. 1. 1. As will be shown later in this section, the amplitude of the V. L. F. oscillations increases with positive or negative bias with respect to the floating potential which is the potential for which the probe draws zero current. Therefore, the spectrum of the V. L. F. oscillations have all been measured with the probe floating. In Figure II. 2. 5 the floating potential and the relative amplitude of the fundamental of the V. L. F. oscillations is plotted versus radial distance. Zero is the position of the cathode surface. The amplitude data has been normalized with the amplitude of the maximum taken to be unity. One notices a well defined maximum at 3 mm from the cathode, i. e. in the negative glow region of the discharge. A second broader maximum of smaller amplitude is observed at larger distances. At high currents this broad maximum disappears. The interpretation of these results in terms of different



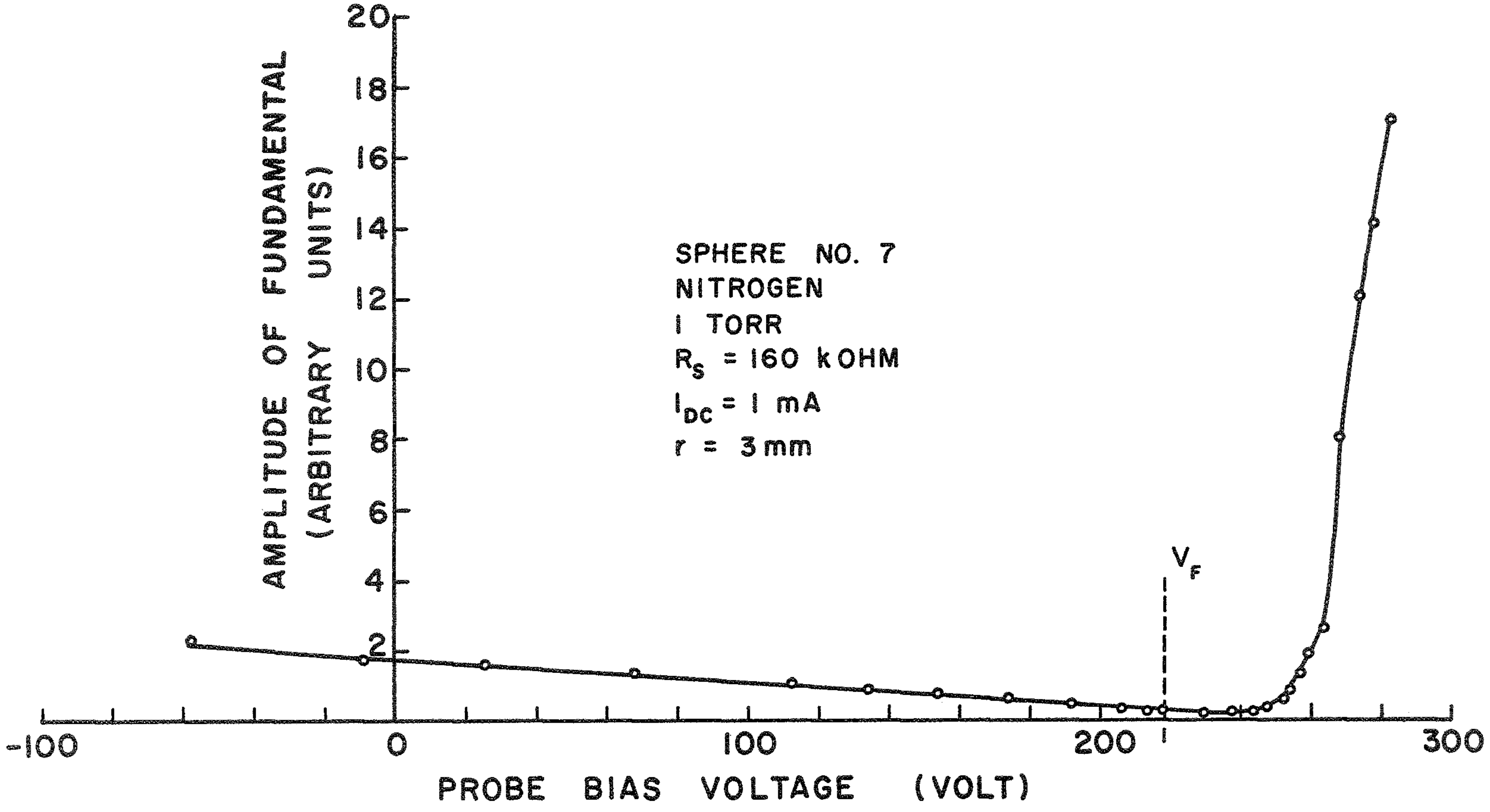
Radial Profile Plot of the Discharge

FIGURE II. 2. 5

modes of oscillation will be discussed later.

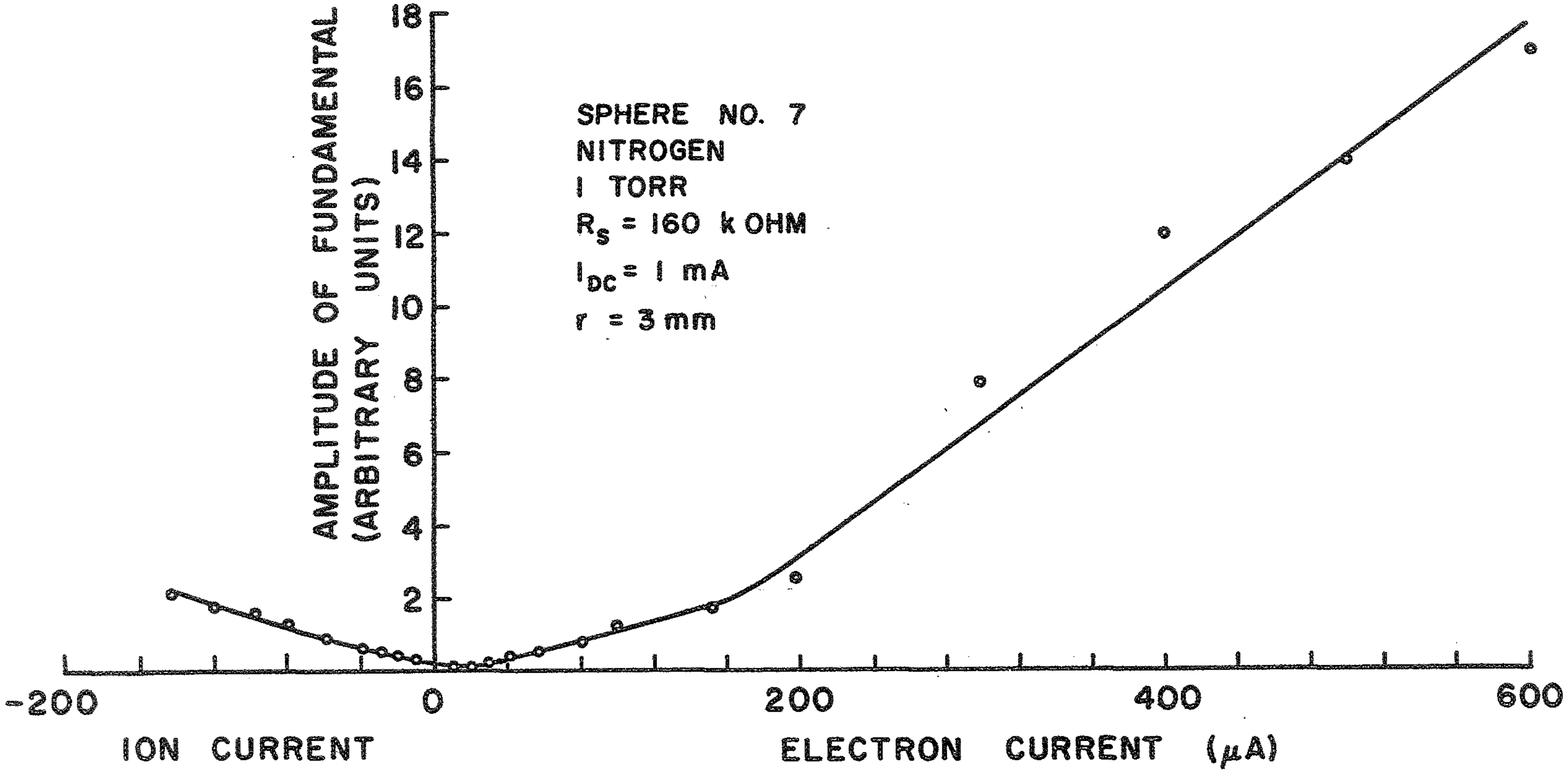
Given the location of the maximum of the plasma oscillations, it is useful to determine which particles, electrons or ions are participating in the oscillations. To provide that information, one can bias the probe positively or negatively with respect to the floating potential and measure the different spectra of the V. L. F. oscillations. From Figures II. 2. 6 and II. 2. 7 it is seen that the magnitude of the fundamental increases for biasing voltages above and below the floating potential. For small ranges of electron and ion current ($\lesssim$ 140 μA), the curve of Figure II. 2. 7 is nearly symmetric and the increase in amplitude is nearly linear. Going beyond that point, one notices that the probe interferes with the discharge, and a decrease of the frequency of the oscillations results. For higher discharge currents, the probe may draw higher currents before that particular interference effect occurs. But in every case, the interference is characterized with a decrease in frequency of the plasma oscillations. Thus, in Figure II. 2. 7, the curve is acceptable up to 140 μA (electron current); beyond that point the frequency shifts to lower values. At 600 μA, the plasma is quenched.

Briefly, no change in frequency is observed in the normal biasing region, i.e. without perturbing the main discharge. It is also observed that the amplitude of the fundamental increases linearly with an increase of ion <u>or</u> electron current, i. e. no preferential biasing direction exists. In other words, ions and electrons are participating in the V. L. F. oscillations.



Amplitude vs Probe Biasing Voltage

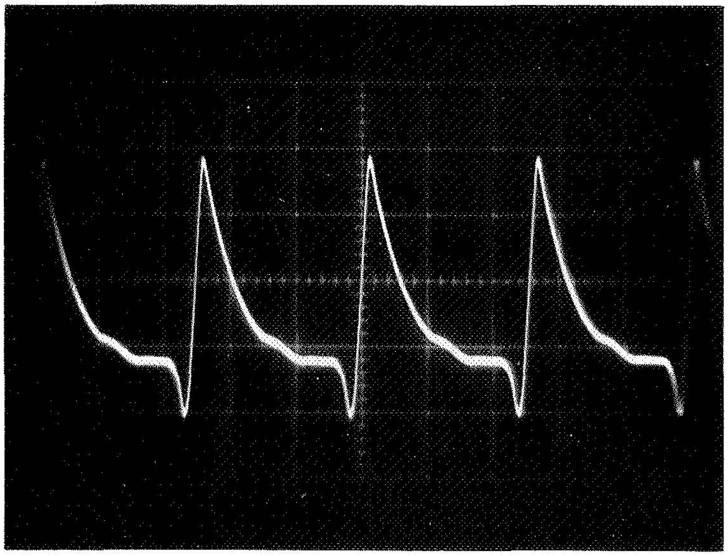
FIGURE II. 2. 6



Amplitude vs Probe Biasing Current

FIGURE II. 2. 7

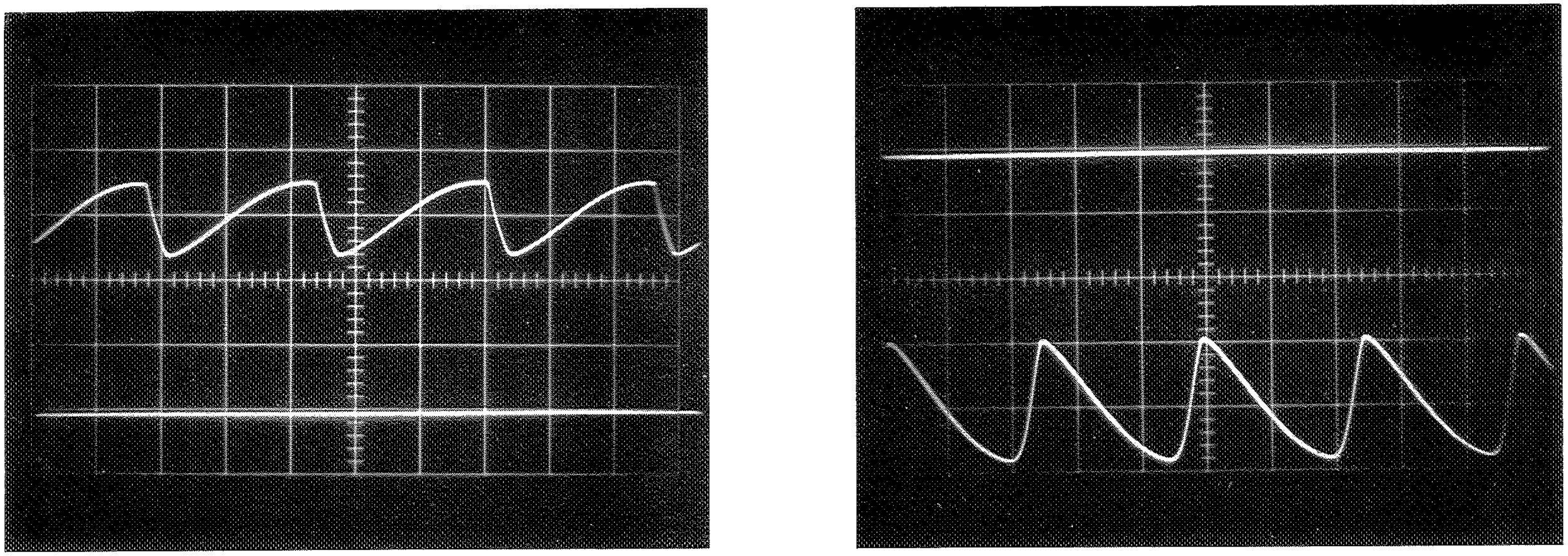
The influence of the bias upon the waveform of the plasma oscillations can be observed in Figures II. 2. 8 and II. 2. 9 a and b. Figure II. 2. 8 shows the waveform for a floating probe. Connecting the probe to the biasing circuit but putting the biasing voltage V_B equal to the floating potential V_F, no change in waveform is seen to occur at this particular frequency. At lower frequency the biasing circuit has a loading and distorting effect as can be seen from Figure II. 1. 5. Figure II. 2. 9 a shows the waveform when $V_B > V_F$. The horizontal trace gives the floating potential V_F as a reference. Figure II. 2. 9 b gives the waveform for $V_B < V_F$. When the probe is biased positively with respect to the floating potential V_F, the probe will locally accelerate the electrons and slow down the ions. If one considers that the V. L. F. oscillations are due to a plasma transport across the magnetic field lines in the equatorial plane around the circumference of the cathode, then one may assume that the electrons will be separated from the ions due to the different collision cross-sections. Thus, the probe tip being biased positively will fall very fast below its DC bias level due to the accelerated electrons. In the next step, the ions will pull the probe potential above its DC bias level but much slower. Vice versa, when the probe is negatively biased with respect to the floating potential, the ions are accelerated and the electrons slowed down. The probe will reach a higher potential than its DC bias in a shorter time then the time necessary to reach a potential lower then its DC bias as can be seen in Figure II. 2. 9 b.



Horizontal scale, 0.1 msec/div.
Vertical scale, 0.2 Volt/div.
V_{DC} = 642 Volt, I_{DC} = 1 mA, R_s = 160 kOhm,
Sphere No. 7, Nitrogen, 1 Torr.

Probe Signal at Floating Potential

FIGURE II. 2. 8



(a)

Horizontal scale, 0.1 msec/div.
Vertical scale, 20 Volt/div. (DC and AC)
V_{DC} = 642 Volt, I_{DC} = 1 mA, R_s = 160 kOhm
Sphere No. 7, Nitrogen, 1 Torr
V_F = 218 Volt (lower trace)
V_B = 278 Volt, I_B = 47 μA

(b)

Horizontal scale, 0.1 msec/div.
Vertical scale, 50 Volt/div. (DC)
Vertical scale, 2 Volt/div. (AC)
V_{DC} = 642 Volt, I_{DC} = 1 mA, R_s = 160 kOhm
Sphere No. 7, Nitrogen, 1 Torr
V_F = 218 Volt (upper trace)
V_B = 18 Volt, I_B = 10 μA

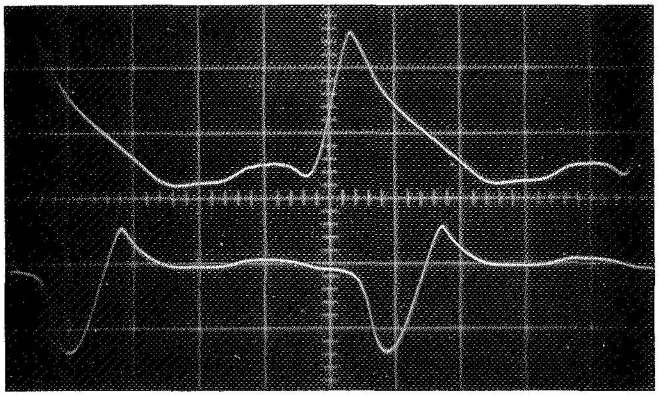
Biased Probe Signals

FIGURE II. 2.9

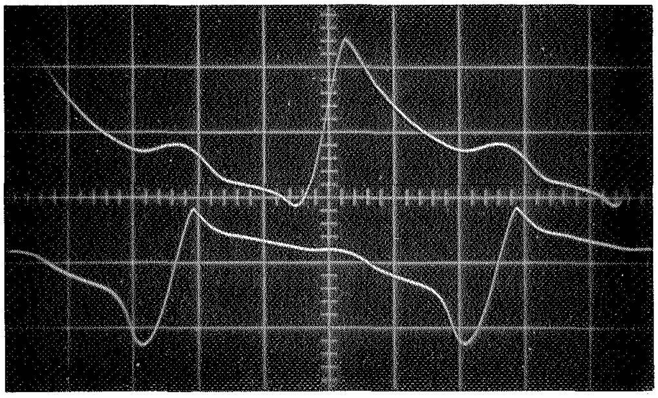
Briefly, in this section we have seen that the maximum of the plasma oscillations is located in the negative glow of the discharge. Further it is pointed out that the plasma oscillations are due to ions and electrons.

II. 2. 3 Time-Delay and Phase Measurements

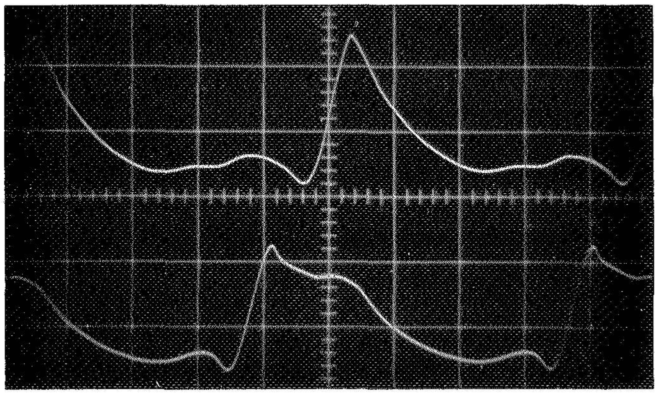
To determine radial variations, the following experiment using the two probe system is performed. One of the two probes is kept fixed in space and is used as the reference signal. This signal is fed into a Tektronix multichannel type M plug-in unit. The output of the channel is used to trigger the oscilloscope. The signal of the second probe which is moving radially is connected to the second channel. As one moves the probe radially, no shift of the waveform with respect to the reference signal is observed, whatever the biasing condition of the probe. For the measurement of the time-delay in the angular direction, the same technique is used. Both probes are placed in the negative glow. A shift of the waveform of the moving probe with respect to the reference probe is observed as shown in Figure II. 2. 10, a to c. The upper trace in the three pictures is the reference signal. One notices that, moving the 2nd probe with respect to the 1st probe, there exists a perturbing effect. The second trace represents the signal of the movable probe. It is observed that the waveform shifts proportional to the angular displacement of the probe from $\theta = 90^{\circ}$, 180° to 270°. This mode of the V. L. F. oscillation is the $m = 1$ mode. The change in waveform of the signal of the 2nd probe is due to the fact that the probe does not



(a): θ = 0°



(b): θ = 180°



(c): θ = 270°

Time-Delay Measurements

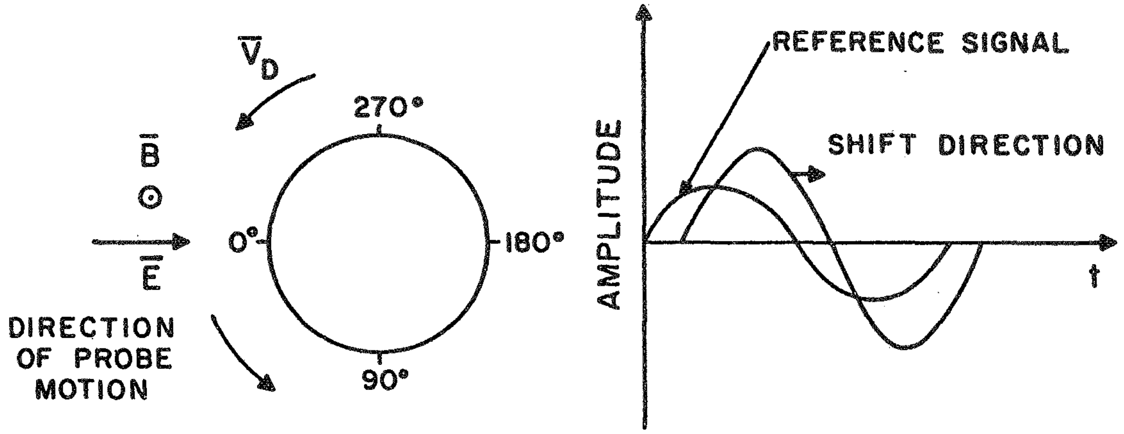
FIGURE II. 2. 10

move exactly in a circular path in the negative glow. In addition, the imperfections of the sphere are reflected in the negative glow which in reality does not have the ideal circular shape.

The measured effect of the polarity of the magnetic field upon the time-delay measurements is shown in Figure II. 2. 11.

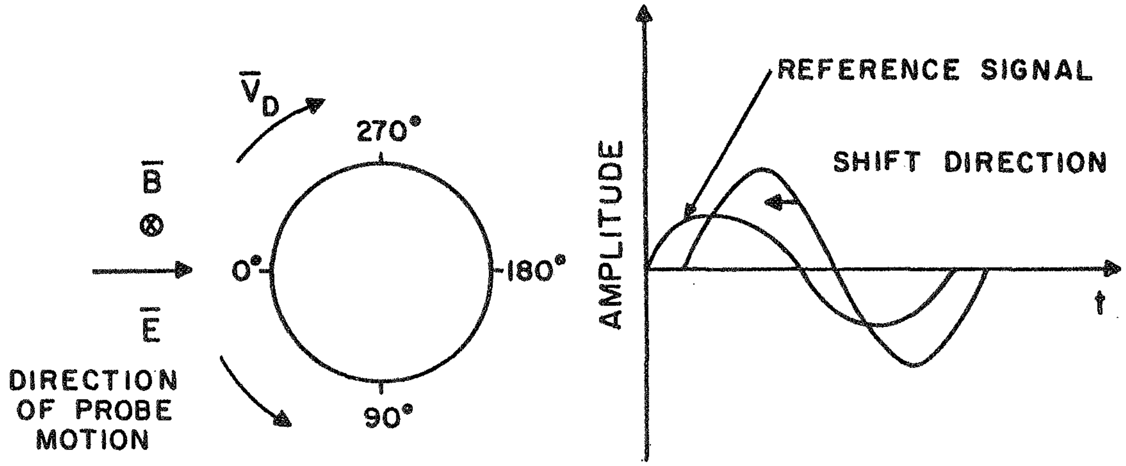
The figure presents a top view of two spheres, the direction of the probe motion and drift velocity, and the measured waveforms. If one considers that there is a transport of plasma across the magnetic field lines given by $\vec{v}_D = \frac{\vec{E} \times \vec{B}}{B^2}$, then a reversal of the magnetic field will cause a reversal of the drift velocity. Now if the direction of the probe motion is maintained the same, this magnetic field reversal will cause a reversal in the shift direction as shown in the figure.

Thus we have observed that there exists no time-delay or advance in the radial direction, but there is a delay (advance) in the angular direction. Namely, there is a 2π shift for a 360° angular displacement of the probe. We call this type of oscillation the $m = 1$ mode. The $m = 1$ mode is always present. At small currents, i.e. $I_{DC} < 1$ mA, a second mode of oscillation exists. This new mode has no phase difference or time-delay in either the radial or angular directions. This mode is called, accordingly, the $m = 0$ mode. A series of pictures is shown for different radial distances in Figure II. 2. 12, a to c. , Each upper trace belongs to the radial moving probe, the lower trace is from the 2nd probe which is fixed at 270°. In the first two pictures the radial probe is biased negatively with respect to



SPHERE NO. 7

(a)

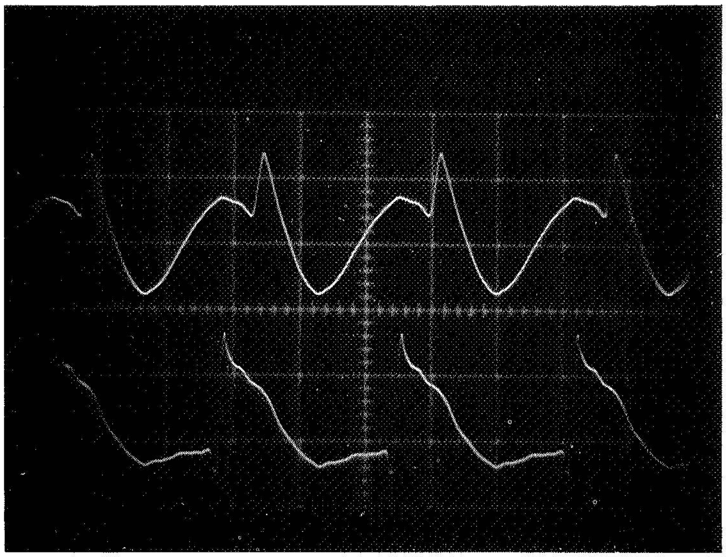


SPHERE NO. 2

(b)

Topview of the Cathode with the Respective Direction of the $\vec{E}$ and $\vec{B}$ Fields and the Appropriate Waveform Shift Direction

FIGURE II. 2. 11



(a)

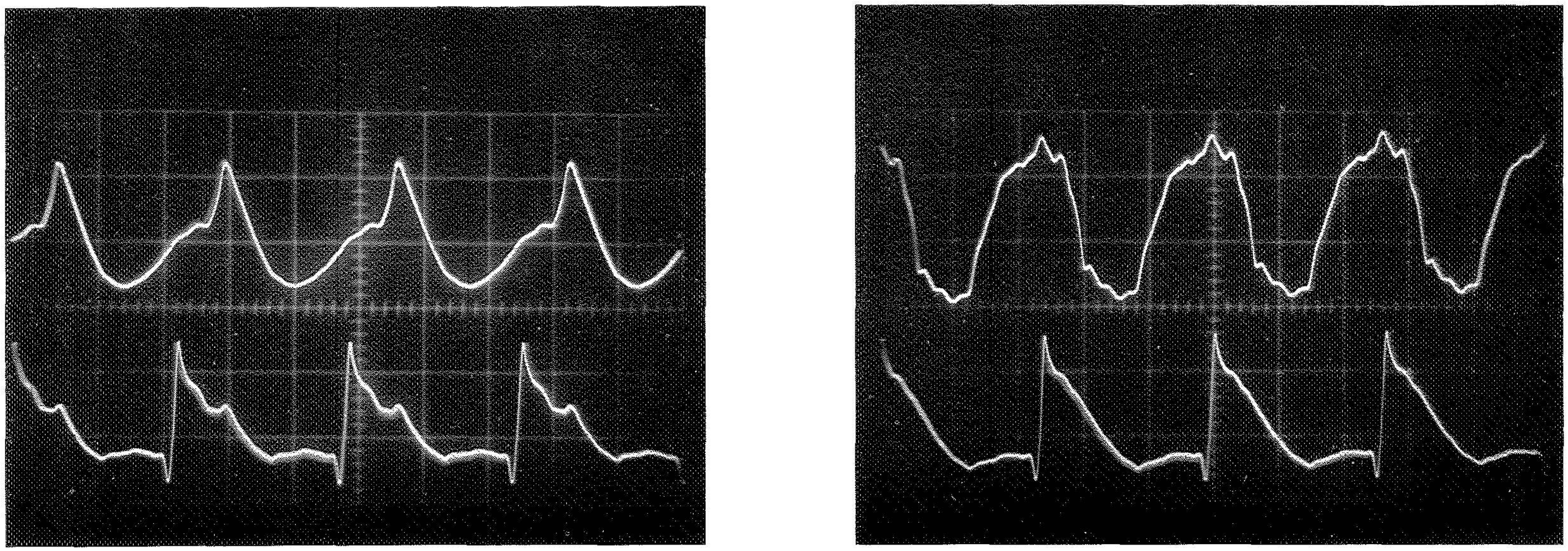
Upper trace: V_B = 182 Volt, V_F = 217 Volt, I_p = 1μA, θ = 0°, r = 2 mm, vertical scale, 1 Volt/div.

Lower trace: Floating probe, θ = 270°, r = 3 mm, vertical scale, 1 Volt/div.

General conditions: Sphere No. 7, 2 Torr, Nitrogen, V_{DC} = 928 Volt, I_{DC} = 0.85 mA, horizontal scale, 0.2 msec/div.

Observation of the m = 0 Plasma Oscillation Mode

FIGURE II. 2. 12



(b)

Upper trace: $V_B = 138$ Volt, $I_p = 1 \mu A$,
$\theta = 0^o$, $r = 5$mm,
vertical scale, 1 Volt/div.

(c)

Upper trace: Floating probe, $\theta = 0^o$,
$r = 11$ mm, vertical scale,
0.2 Volt/div.

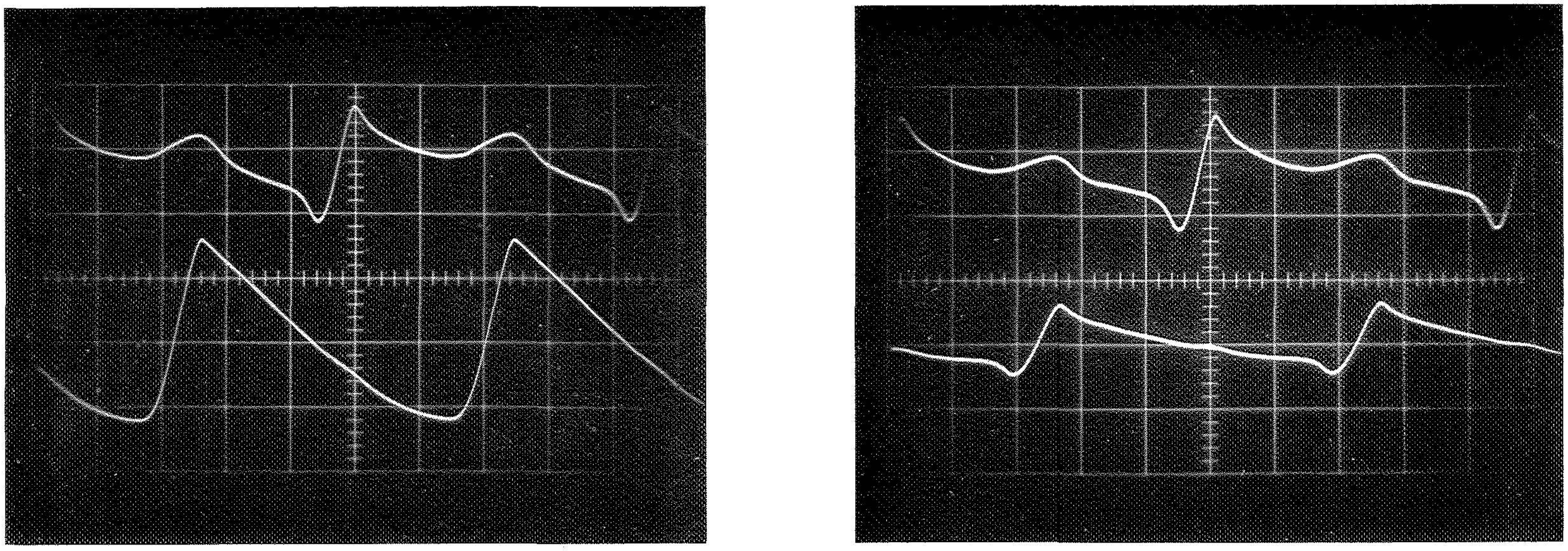
Lower trace specifications and general conditions as under (a)

Observation of the m = 0 Plasma Oscillation Mode

FIGURE II. 2. 12 (Cont'd)

the floating potential in order to make the $m = 0$ appear more clearly. It is seen that the $m = 1$ mode is superimposed on the $m = 0$ mode. The $m = 1$ mode shows a phase difference while the $m = 0$ is in phase. Both modes of oscillations have the same frequency. In picture (c) the radial probe is floating. It shows that away from the cathode surface ($r = 11$ mm) the disturbing influence of the $m = 1$ mode decreases and the $m = 0$ mode is clearly observed. The second trace giving the signal of the probe placed at 270° at approximately 2 mm from the cathode shows clearly the $m = 1$ mode partially masking the $m = 0$ mode.

Finally the probe signal was studied under different biasing conditions to determine if biasing causes a phase change. No phase shift was observed. Also it was observed as previously discussed that the effect on the waveforms at $V_B < V_F$ and $V_B > V_F$ are symmetric. A series of pictures are given in Figure II. 2. 13, (a) to (d) showing the change in waveform. It was also verified that the biasing circuit does not load down the signal or introduce a phase shift.



(a)

Upper trace; reference signal,
Vertical scale, 1 Volt/div.
Lower trace: V_B = 168 Volt, I_p = 5 μA
Vertical scale, 1 Volt/div.
General conditions: V_{DC} = 642 Volt,
I_{DC} = 1 mA, Nitrogen, R_s = 160 kOhm,
Sphere No. 7, 1 Torr.
Horizontal scale, 50 μsec/div.

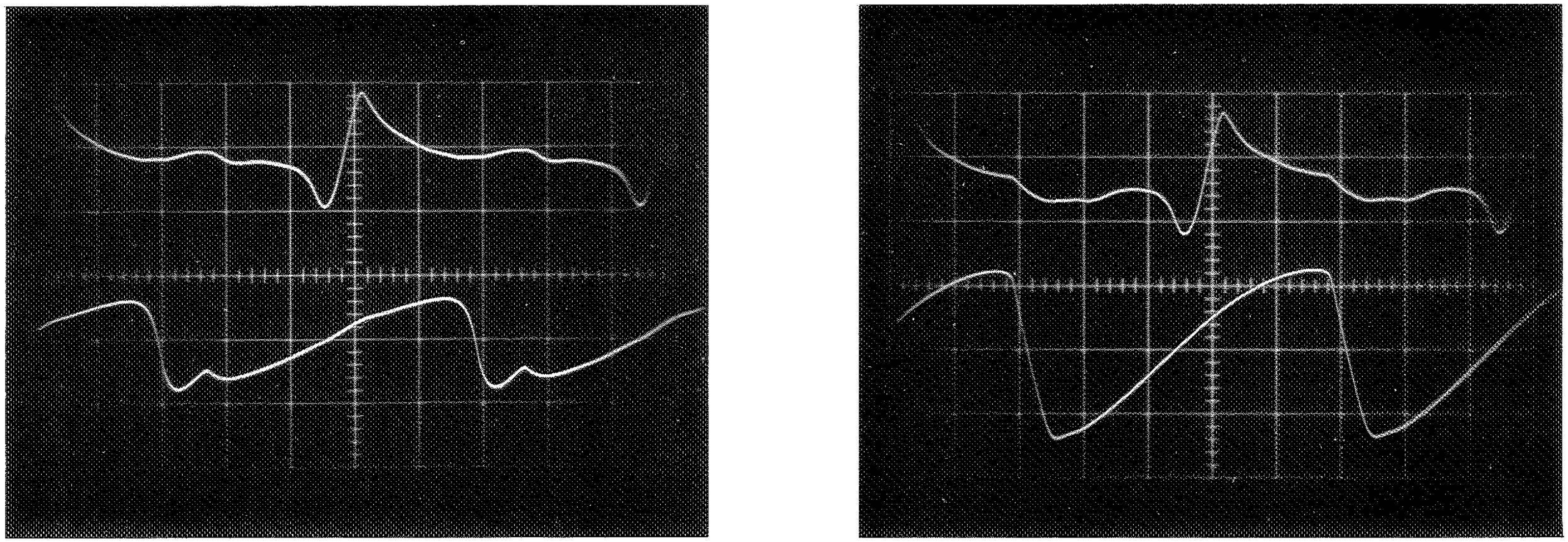
(b)

Upper trace: as under (a)

Lower trace: $V_B = V_F$ = 222 Volt, I_p = 0 μA,
Vertical scale, 1 Volt/div.
General conditions: as under (a)

Investigation of Phase Shift for Various Biases

FIGURE II.2. 13



(c)

Lower trace: $V_B = 248$ Volt, $I_p = 5\ \mu A$
Vertical scale, 1 Volt/div.

(d)

Lower trace: $V_B = 260$ Volt, $I_p = 30\ \mu A$
Vertical scale, 5 Volt/div.

Upper trace specifications and general conditions as under (a)

Investigation of Phase Shift for Various Biases

FIGURE II. 2. 13 (Cont'd)

II. 3 REVIEW OF CONCLUSIONS

Using probes as a diagnostic tool we have obtained the following information.

Two different modes of V. L. F. oscillations exist. The m = 1 mode is the most easily observed under a wide range of discharge and pressure conditions. The m = 0 mode, i. e. no time-delay or advance in either the radial or the angular directions, appears clearly at low current levels. It is found that both modes have the same frequency. Finally the maximum of the plasma oscillations is located in the cathode glow, and both ions and electrons are participating in the motion.

III. DERIVATION OF A SIMPLE THEORETICAL MODEL

In Table III. 1 the conclusions of the experimental investigation have been compiled for easy reference.

We have found two sets of experimental evidence indicating that there is a plasma transport across the magnetic field lines. First, it is noticed that a revolving plasma dot exists at low currents for argon as the residual gas at 1 and 2 Torr. The same phenomenon is observed with nitrogen and air but under other discharge and pressure conditions. The rotation of this dot can be controlled by changing the power supply to higher voltages or lower currents. There exists a threshold voltage (current) below (above) which the dot is fixed in space. A sketch of this simple physical model is given in Figure III. 1

The second experimental observation indicating a plasma transport perpendicular to the magnetic field lines is the detection of time-delays in the θ direction for the $m = 1$ mode.

As a demonstration of the sense of direction of the plasma transport across the magnetic field lines, the following experiment was performed. A probe was placed near the surface of the cathode in the negative glow region of the discharge. Grounding the probe had the effect of interrupting the flow. In other words the negative glow region did not extend around the complete circumference of the cathode. The length of the arc going around the sphere is determined by the bias condition of the probe in question. Reversing the magnetic field, the arc directed itself in the opposite direction. Results of

TABLE III. 1

Summary of the Experimental Observations*

PARAMETER	FREQ.	REMARKS
↗ I_{DC}	↘	↗ Amplitude
↗ V_{DC}	↗	↘ Amplitude
↗ Pressure	↘	↗ Amplitude
↗ R_s	—	L.F. Suppressed
↗ B	—	—
↗ Cathode Diam.	↘	FUND < 2nd HARM
↗ Atomic Weight	↘	a) ARGON Oscil. Visible b) HELIUM Various Modes Internal Mod.

AND

a) NOISE SOURCE LOCATED NEAR THE CATHODE

b) IONS AND ELECTRONS PARTICIPATE IN THE OSCILLATIONS

c) A $2m\pi$ PHASE SHIFT IN THE θ DIRECTION

$m = 0$ FOR LOW CURRENTS

$m = 1$ FOR HIGH CURRENTS

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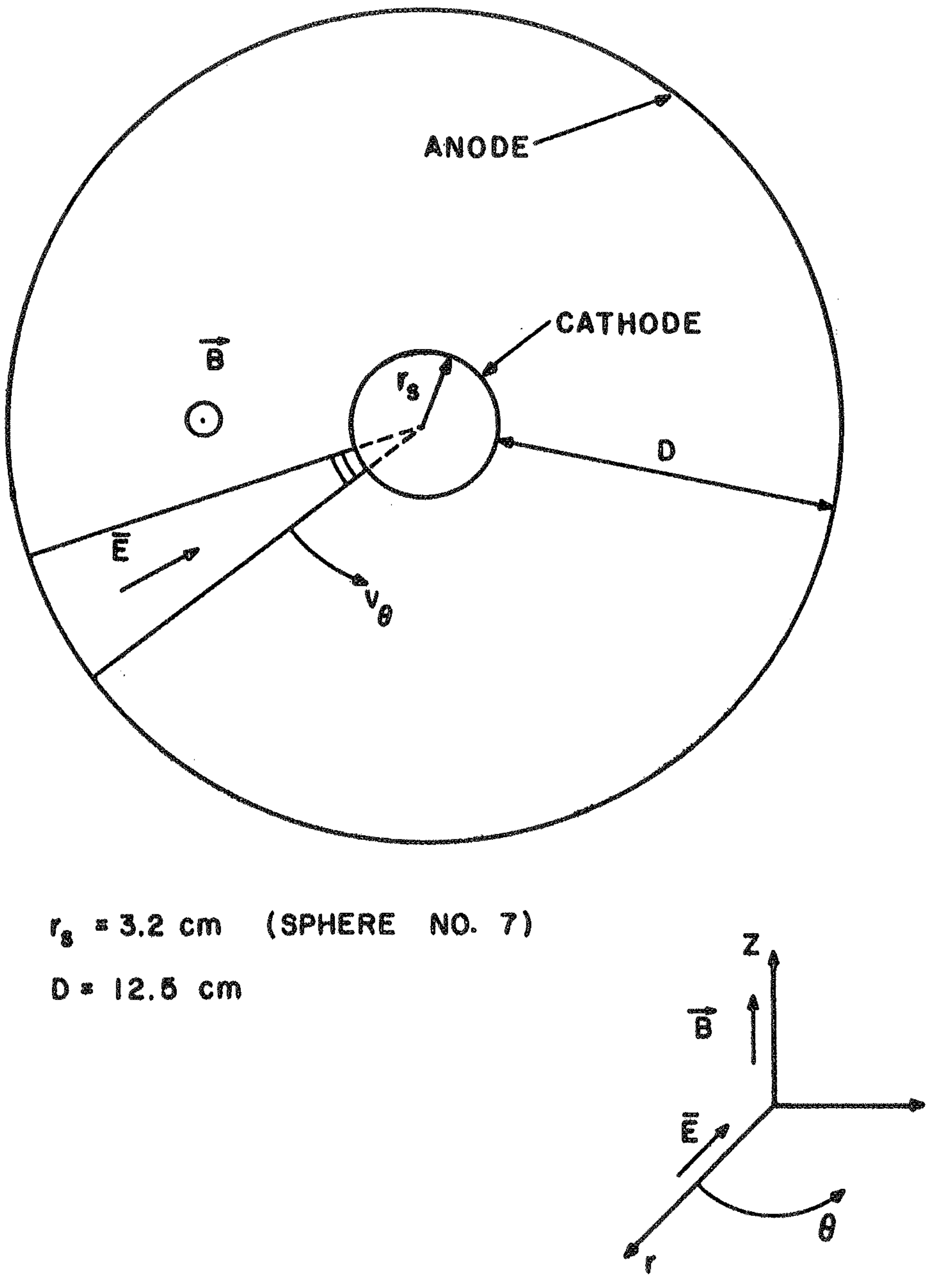
*Note that the table includes also the results obtained previously by Schmidt and Quinn (1969).



r_s = 3.2 cm (SPHERE NO. 7)

D = 12.5 cm

Simple Physical Model

FIGURE III. 1

this particular experiment is shown in pictures (a) and (b) of Figure III. 2.

In what follows, we assume that the magnitude of the wave vector $\vec{k}$ may be written as

$$k = \frac{2\pi}{d} \tag{1}$$

where d is the length of the negative glow in the θ direction, or approximately the equatorial circumference of the cathode. The experimental basis for these assumptions is the fact that the frequency increases with decreasing diameter of the cathode and that the maximum of the oscillations is located in the negative glow region.

Further we postulate for the frequency of rotation of the plasma in the equatorial plane the following relationship

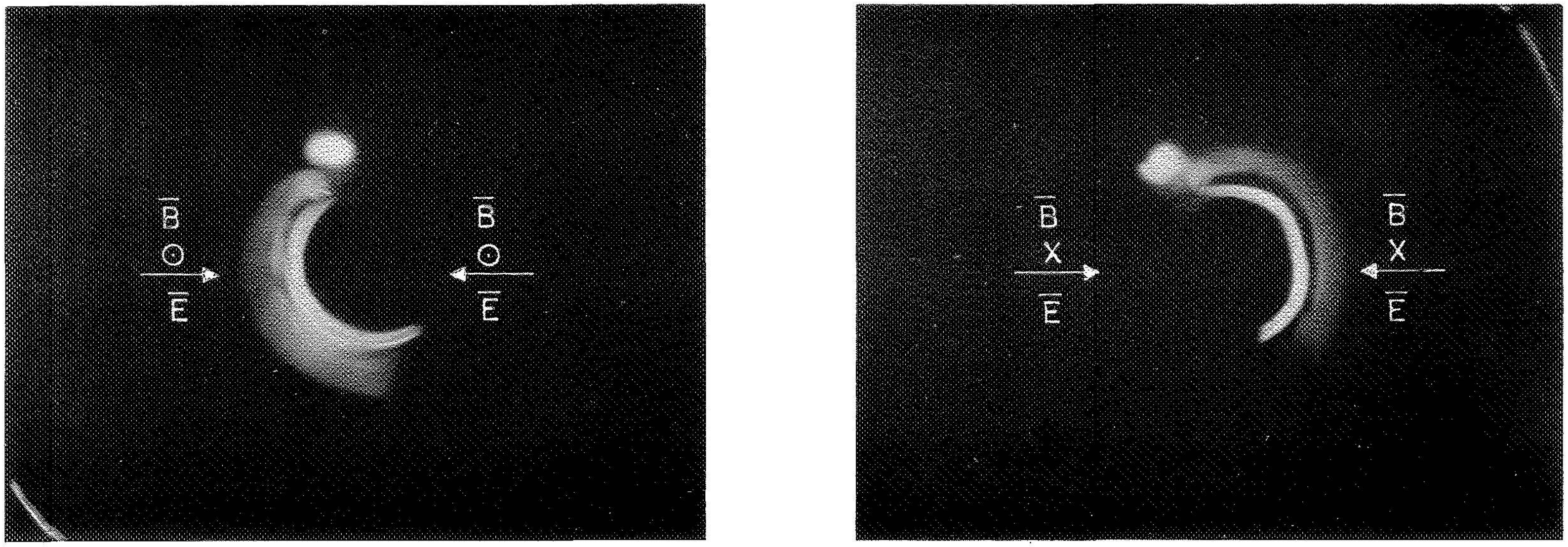
$$\omega = kv_D \tag{2}$$

where ω is the angular frequency of rotation and v_D is the drift velocity.

Much of the observed experimental dependence on pressure and mass can be found by assuming the frequency of oscillation is proportional to the rotation frequency of the plasma. In addition, the rotation of the dot implies a rotation of electrons which are exciting the neutrals. The simplest description appropriate to the system is use of the Langevin equation for both electrons and ions. This implies a neglect of the pressure gradient, an approximation which is clearly valid for ions but may be questionable for electrons.

The Langevin equation is written as follows

$$m\frac{d\vec{v}}{dt} = -q\,(\vec{F} + \vec{v} \times \vec{B}) - m\nu\vec{v} \tag{3}$$



(a)

South-North aligned sphere

(b)

North-South aligned sphere

Interruption of the Negative Glow by Means of Grounded Probe

FIGURE III. 2

where m is the mass of the species, q the charge of the species, $\vec{v}$ the velocity, $\vec{E}$ the electric field, $\vec{B}$ the magnetic field, and ν the collision frequency with the neutrals.

Using a cylindrical coordinate system to describe the behavior on the midplane and neglecting the motion along the field lines and the $\vec{v} \cdot \vec{\nabla} v$ term, one obtains for the stationary case

$$- m \frac{v_\theta^2}{r} = q E_r + q v_\theta B_z - m\nu v_r \qquad (4)$$

$$m v_r \frac{v_\theta}{r} = -q v_r B_z - m\nu v_\theta \qquad (5)$$

Using equations (1) and (2), equations (4) and (5) can be written as follows

$$- \omega^2 = r\Omega\omega + \frac{qE_r}{rm} - \nu v_r \qquad (6)$$

$$v_r \omega = -\Omega v_r - r\nu\omega \qquad (7)$$

where $\omega = v_\theta / r$.

In the negative glow region of the discharge, we have typically $B = 0.05$ Wb/m^2 so that $\Omega_e = 8.8 \times 10^9$ radians/sec. and $\Omega_i = 1.7 \times 10^5$ radians/sec. for molecular nitrogen. Furthermore, at 1 Torr, $\nu_{en} \simeq 1.23 \times 10^{10}$ collisions/sec. and $\nu_{in} \simeq 9.42 \times 10^6$ collisions/sec. At this pressure, low frequency oscillations occur with frequencies $0 < \omega < 10^5$ radians/sec. Restricting the discussion to frequencies below 2×10^4 radians/sec. the following conditions are satisfied for both electrons and ions:

$$\omega < \Omega \qquad (8)$$

The left hand side of equations (6) and (7) may therefore be neglected with respect to the first term of the right hand side of the equations. One obtains then that

$$\omega = \frac{2\pi}{d} \frac{\Omega^2}{\Omega^2 + \nu^2} \frac{E_r}{B_z} \qquad (9)$$

$$v_\theta = \frac{\Omega^2}{\Omega^2 + \nu^2} \frac{E_r}{B_z} \qquad (10)$$

For ions it should be noted that $\nu \gg \Omega$ so that

$$\omega = \frac{2\pi}{d} \frac{q^2}{m^2 \nu^2} \quad E_r \quad B_z \qquad (11)$$

$$v_\theta = \frac{q^2}{m^2 \nu^2} \quad E_r \quad B_z \qquad (12)$$

From equation (10) it can be shown that

$$v_{\theta e} \gg v_{\theta i}$$

This would tend to indicate that the electrons were playing the dominant role, and the ions were passive. This is not in agreement with experimental results which show that the oscillations are dependent on ion mass and that both species participate. However, it may be that the difference in drift velocities represents the driving energy for the instability, as one finds, for instance, for the two-stream instability. It will be necessary to develop a more elaborate two or three fluid model to properly determine the role each species plays.

From our observations of a plasma transport across the magnetic field lines, we assume that the bulk motion has the velocity of the ions. So that, we may use equation (11)

$$\omega = \frac{2\pi}{d} \frac{e^2}{m^2 \nu^2} E_r \ B_z$$

Applying above formula in the negative glow region of the discharge with $E_r \simeq 7.5 \times 10^4$ v/m, $B_z = 5 \times 10^{-2}$ Wb/m^2 and $d = 2\pi r$ where $r = 3.2$ cm, it is found that $\omega \simeq 1.5 \times 10^4$ radians/sec.

This simplified model is consistent with a great deal of the experimental evidence. First, the frequency of oscillations calculated using the experimental values agrees with those measured. The observed decrease in frequency with increasing ion mass, pressure and cathode diameter is predicted.

Due to the fact that it was not possible to observe any frequency dependence on the magnetic field in the previously reported experiments, a new plasma device has been developed. An anode and cathode were formed by two concentric cylinders. A uniform magnetic field was applied parallel to the axis of the cylinders. This arrangement provides for the elimination of a radial gradient and curvature of the field as well as a continuously variable magnetic field. It was observed that the oscillations do not exist for B = 0. However oscillations occur when a field is applied, and the frequency is linearly related to the applied field as predicted by our simple model.

It has been observed that the frequency increases with decreasing current. A study of the variation in the Figure 3.12 given in the paper by Schmidt and Quinn (1969) indicates that there are two distinct frequency ranges. At the low frequency side, the frequency is not very sensitive to a change in current. While at the high frequency side, small changes in current cause large frequency changes. This particular behavior is not predicted in the simple model developed here.

IV. SUMMARY AND SUGGESTIONS FOR FURTHER STUDY

Low frequency oscillations have been observed in a cold cathode discharge having a uniformily magnetized spherical cathode. The phenomena were examined experimentally using various diagnostic techniques. Treating the system as a two terminal device (Schmidt and Quinn, 1969) the effects of pressure, ion species, cathode diameter, magnetic field and external circuit resistance were determined. An external antenna was used to detect and monitor the oscillations during all of the experiments. It was discovered that a mixing effect could be achieved using this antenna. Probes immersed in the plasma were used in this study to determine the spatial characteristics of the oscillations. The experimental results are summarized in Table III. 1. A simple theory has been developed which explains much of the experimental data.

There are a number of areas which need further investigation. First, there is a need to develop a more sophisticated theoretical model.

Simon (1963) and Hoh (1963) analyzed the $\vec{E} \times \vec{B}$ instability, and Aldridge (1970) adopted the Simon model to find a relation between the frequency of rotation of a plasma column with the frequency of the oscillations. On the other hand, Buneman (1963) suggested the possibility of the excitation of field aligned sound waves by means of electron streams. The ions would play the coupling role between the electrons and the neutrals. The condition used in his analysis

$$\nu_{en} m_e << eB << \nu_{in} m_i$$

is not valid for our experiment. Namely, it is found that the cyclotron frequency is smaller than the collision frequency for both species, so that the above condition has to be modified accordingly.

It is not clear yet which of the two mentioned mechanisms is responsible for the observed phenomena.

The progress of any theoretical development will of course be greatly enhanced by further experimental work. There are quite a few experimental investigations which offer the possibility of gaining significant new information.

One class of experiments is utilizing a cylindrical anode - cathode configuration in sealed glass tubes which are placed in a variable magnetic field. Such devices would provide the capability of maintaining constant pressure and high purity for extended periods of time. This would enable one to obtain quantitative data concerning the effect of ion species and pressure and allow a thorough investigation of the anamolous helium modes. In this respect, the phenomenon has an obvious potential application as the basis for a highly sensitive vacuum gauge.

The observed mixing effect (Schmidt and Quinn, 1969) should be critically examined experimentally as it is potentially important in the area of feedback control of various "drift type" instabilities as mentioned by Parker et. al. (1969(and Keen et. al. (1969) and Keen (1970).

Von Engel (1955) describes an experiment in which a plane cathode is rotated. On the basis of this experiment, it was concluded that the negative glow rotates with the cathode while the positive column remains fixed. It would be extremely useful to study the effect of rotation on the frequency of the oscillation of both the m = 0 and the m = 1 modes.

The effects of electric fields and density gradients can be studied with more versatile devices having cylindrical geometry. The work by Caron (1969) suggests a method of controlling the conditions within the discharge using mesh grids. Following a suggestion by Quinn (1968) a thermal plasma formed by contact ionization could be used to study the effects of gradients and electric fields in detail.

Using the above devices and suggestions, one might expect to gain significant new information.

BIBLIOGRAPHY

Aldridge, R. V. and B. E. Keen, "Rotationally Convected Drift Wave Instability in an Inhomogeneous Plasma Column," Plasma Physics, 12, 1, 1970.

Buneman, O., "Excitation of Field Aligned Sound Waves by Electron Streams," Phys. Rev. Letters, 10, 285, 1963.

Caron, P. R., "A Technique for Generating Well-Behaved Plasmas in a Waveguide," Proc. I.E.E.E., 57, 1672, 1969.

Hoh, F. C., "Instability of Penning-Type Discharges," Phys. Fluids, 6, 1184, 1963.

Keen, B. E., "Interpretation of Experiments on Feedback Control of a Drift-Type Instability," Phys. Rev. Letters, 24, 259, 1970.

Keen, B. E., and R. B. Aldridge, "Suppression of a Drift-Type Instability in a Magnetoplasma by a Feedback Technique," Phys. Rev. Letters, 22, 1358, 1969.

Parker, R. R. and K. I. Thomassen, "Feedback Stabilization of a Drift-Type Instability," Phys. Rev. Letters, 22, 1171, 1969.

Quinn, R. G., "Description of Space Simulation Experiments Utilizing Plasma Produced by Contact Ionization," The Pennsylvania State University, I.R.L. Scientific Report No. 331, 1968.

Schmidt, P. E. and R. G. Quinn, "Plasma Oscillations in a Spherical Magnetized, Cold Cathode Discharge, "The Pennsylvania State University, I.R.L. Scientific Report No. 341, 1969.

Simon, A., "Instability of a Partially Ionized Plasma in Crossed Electric and Magnetic Fields," Phys. Fluids, 6, 382, 1963.

von Engel, A., Ionized Gases, Oxford University Press, 1955.