AN ABSTRACT OF THE THESIS OF

Vernon Edgar Golden for the M. S. in Physics
(Name) (Degree) (Major)

Date Thesis presented May 12, 1951

Title THE EFFECT OF PRESSURE ON WAVELENGTHS OF PLASMA OSCILLATIONS IN ARGON AND NITROGEN

Abstract Approved [redacted]
(Major Professor)

Experiments on argon and nitrogen are described which show that the wave length of electromagnetic radiation emitted from a gas plasma in a magnetic field is a function of the pressure of the gas. This result is consistent with the theory of plasma oscillation developed by Tonks and Langmuir if the assumption is made that plasma electron density is a function of gas pressure. A lower limit of wave length of plasma oscillation is indicated by the experiments in qualitative agreement with the Debye length equation. No difference in the wave length-pressure relationship between the two gases was observed.

The experimental tube, which consisted of a gas filled cylindrical anode with an axial tungsten filament, was mounted in a magnetic field parallel to the axis of the anode. Gas pressures between 1 and 50 microns and magnetic fields between 500 and 1,000 gauss were used.

The anode voltage was applied in short pulses in order to minimize heating of the cathode by ion bombardment and to make possible the use of alternating voltage amplifiers in the receiver.

The receiver of electromagnetic radiation consisted of a crystal-detector dipole, constructed from a IN26 crystal cartridge, followed by a video amplifier. The amplifier had a maximum gain of 1.6×10^7, and a bandwidth of 2 megacycles. Wave lengths were measured by means of an interferometer.

THE EFFECT OF PRESSURE ON THE WAVE LENGTH OF PLASMA OSCILLATIONS IN ARGON AND NITROGEN

by

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A THESIS

submitted to

OREGON STATE COLLEGE

in partial fulfillment of
the requirements for the
degree of

MASTER OF SCIENCE

June 1952

APPROVED:

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Date thesis is presented June 15, 1951

Typed by Evelyn Davis

ACKNOWLEDGMENT

I wish to express my appreciation to Dr. E. A. Yunker for his guidance and assistance throughout the investigation and the writing of this thesis; Dr. J. J. Brady for his helpful criticism of the thesis contents; the United States Air Force for permission to use the facilities of the Physics Department Millimeter Wave Project; and to Mr. John Barbour for his assistance in taking data when two operators were required.

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INTRODUCTION

A gas plasma is defined as a region in a gas in which there exists equal concentrations of positive and negative charges. Plasmas are found in the ionized atmospheres of the stars and planets as well as in the atmosphere of the earth. They also exist in gas or vapor discharge tubes in which case the negative charges are electrons.

Plasma oscillations consist of vibratory motions of the particles in the gas plasma. These particle vibrations give rise to longitudinal waves, analogous to sound, and transverse waves which in some cases may give rise to electromagnetic radiation.

Plasma oscillations are of particular interest to radio engineers, astronomers, and physicists. For example, Bailey (1) has treated some of the problems of plasma oscillations on the sun's surface. These oscillations are detected at the earth as circularly polarized electromagnetic radiations. Mimno's (19) treatment of radio-frequency propagation through, and reflection from, the ionosphere involves plasma vibrations.

Because of the electrical interactions between plasma charges, there is a resultant orderly arrangement of the particles which permits a relatively simple mathematical approach to the detailed motion of the individual particles.

As a result of the orderly arrangement, and the equal numbers of positive and negative charges, the plasma tends to remain field-free and electrically neutral. Any external field or incomplete space charge distribution will tend to be compensated by the mobile ions in the plasma. Thus if any disturbance, such as a displacement of a charge, occurs in this ionized region, there will result an electrical stress causing a force of restitution on the charge which in turn will cause the particle to oscillate with linear simple harmonic motion. These oscillations are analogous to those occuring in sound. The frequency of oscillation is given by:

$$\nu = \frac{e}{2\pi}\sqrt{\frac{n}{Km}} = 8980\sqrt{n} \text{ cycles per second.}$$

where $n =$ electron density in electrons meter^{-3}

and $K = \dfrac{10^{-9}}{36\pi}$ farad meter^{-1}

The derivation of this equation, which will be given later, was first made by Tonks and Langmuir (22).

Theories of plasma oscillation have been developed by a number of investigators (2,3,4,9,11,15,16,17). However, that presented by Tonks and Langmuir is perhaps basic to all others. They performed some experiments in which probes were placed in the plasma region of a mercury vapor arc discharge. By applying a potential difference between a hot cathode and a plane anode, electron densities in the order of 10^{10} electrons cm^{-3} were obtained. By utilizing a zincite-tellurium crystal detector, electromagnetic radiations having frequencies of 1000 mc: 100 mc: and 1.5 mc were obtained. These frequencies were due to ultimate electrons, beam electrons, and positive ions respectively and were found to obey the equation given above.

The beam electrons are those having energies obtained from the electric field and from thermal emission from the cathode. The ultimate electrons obtain their energies from collisions, other thermal motions in the plasma, and secondary emission.

Langmuir's work indicates that there are two distinct types of oscillations occuring in the plasma region, namely electronic and ionic. The electronic oscillations are so rapid that the ions cannot follow, while the oscillations of the ions are so slow that the electron velocities continually satisfy the Boltzmann distribution law. Each of these two types may be sub-divided into transverse and longitudinal oscillations.

The equation for plasma oscillations may be derived from Maxwell's Equations, i.e.:

$$\nabla \times H = j_c + \frac{\partial D}{\partial t} \qquad \nabla \cdot D = \rho$$

$$\nabla \times E = -\frac{\partial B}{\partial t} \qquad \nabla \cdot B = 0$$

$$F = -eE - ev \times B$$

WHERE

$\frac{\partial D}{\partial t} = \dot{D}$ = DISPLACEMENT CURRENT DENSITY

$\dot{j}_c = -nev$ = CONDUCTION CURRENT DENSITY

n = ELECTRON DENSITY

e = ELECTRON CHARGE

v = VELOCITY

$D = \kappa E$, E = ELECTRIC FIELD INTENSITY

$B = \mu H$ = MAGNETIC INDUCTION

H = MAGNETIC FIELD INTENSITY

ρ = CHARGE DENSITY

μ = MAGNETIC PERMEABILITY OF FREE SPACE

κ = PERMITIVITY OF FREE SPACE

FROM $\nabla \times H = -nev + \dot{D}$

WE GET $v = \frac{-\nabla \times H + \dot{D}}{ne}$

$$\dot{v} = \frac{d}{dt}\left(\frac{-\nabla \times H + \dot{D}}{ne}\right)$$

THEREFORE $F = m\dot{v} = -eE - ev \times B$

$$-eE - ev \times B = m\frac{d}{dt}\left(\frac{-\nabla \times H + \dot{D}}{ne}\right).$$

ASSUMING NO MAGNETIC FIELD AND THAT $\frac{dn}{dt} = 0$

WE HAVE $v \times B = 0$, $\frac{dH}{dt} = 0$.

WE MAY NOW WRITE

$$-eE = \frac{m}{ne}\ddot{D} \quad \text{or} \quad \ddot{E} + \frac{ne^2}{Km}E = 0$$

FROM WHICH WE GET

$$\omega^2 = \frac{ne^2}{Km} \quad \text{or} \quad \nu = \frac{e}{2\pi}\sqrt{\frac{n}{Km}} \ \text{SEC.}^{-1}$$

SINCE $\omega = 2\pi\nu$ = ANGULAR FREQUENCY.

THUS FOR AN ELECTRON DENSITY OF 10^{10} CM.^{-3},

$\nu = 9.0 \times 10^8$ CYCLES PER SECOND.

The absence of space coordinants in the equation

$$\ddot{E} + \frac{ne^2}{Km}E = 0$$

shows that there is no propagation through the plasma and that their group velocity is zero.

Tonks and Langmuir (22) theorized that there are three methods possible for transmitting electronic oscillations through a plasma. The first is that oscillating electrons move as a group through the plasma. If we consider the beam electrons for this case and assign a value 3.1×10^{-4} amperes cm^{-2} as the current density, and 5.1×10^8 cm sec^{-1} as the electron velocity, we arrive at a charge density of 6.1×10^{-13} coulombs cm^{-3} corresponding to an electron density of 3.8×10^6 electrons cm^{-3} and therefore a plasma-electron frequency of 1.8×10^7 sec^{-1}.

The second possibility is that the electric field of the oscillation will reach through the discharge region and past the plasma boundaries. This is the field that would be detected beyond the tube envelope.

The third possibility is that oscillations in some parts of the plasma will cause the beam electrons to be accelerated in rhythm which in turn will excite neighboring portions of the plasma.

There are two possible factors which may cause a deviation from the theory outlined above for the plasma-electron oscillations. The first is the Doppler effect; the second the random motions of the electrons at thermal velocities.

Bohm and Gross (2,3,4) found that when thermal motions, long wave lengths, and a Maxwellian distribution of electron velocities are considered, a steady state dispersion relation can be obtained, from which

$$\lambda = 4\pi\sqrt{\frac{3KT}{(\omega^2-\omega_p^2)m}}$$

where

ω = angular frequency of the electrons

ω_p = plasma angular frequency = $\sqrt{\frac{ne^2}{Km}}$

λ = wave length

K = Boltzmann's constant

T = electron temperature.

The ability of the plasma to "shield out" coherent oscillations is limited by the Debye length (7), the reciprocal of which corresponds to an absorption coefficient of an ionized fluid for electric forces. The value of the Debye length, λ_D , as derived by Debye and Huckel, is given by

$$\lambda_D = \left(\frac{KT}{8\pi n e^2}\right)^{1/2} = 4.90\left(\frac{T}{n}\right)^{1/2} \text{cm.}$$

The significance of the Debye length may best be seen through a derivation of an equation (7, 22).

The relation between the electrostatic potential and the charge density at any point is given by Poisson's equation, based on Coulomb's law. If this relationship may be assumed to apply to ions, then

$$\nabla^2 \psi = -\frac{4\pi\rho}{D}$$

where D is the dielectric constant of the medium, ρ the charge density, and ψ the electrostatic potential. Converting to polar coordinates, and making use of the fact that the terms containing $\frac{\partial \psi}{\partial \theta}$ and $\frac{\partial \psi}{\partial \phi}$ will be zero, since the distribution of potential about any point in the electrolyte is spherically symmetrical, the equation becomes

$$\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 \frac{\partial \psi}{\partial r}\right) = -\frac{4\pi\rho}{D} .$$

Introducing the value for ρ which may be written $\rho = -\frac{e^2 \psi}{KT} n$,
we have

$$\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 \frac{\partial \psi}{\partial r}\right) = \frac{4\pi e^2}{DKT}\psi n = \frac{1}{\lambda_D}\psi.$$

The general solution of this differential equation, whereby ψ may be expressed in terms of the distance r from the given ion, is

$$\psi = \frac{A e^{-r/\lambda_D}}{r} + \frac{A' e^{r/\lambda_D}}{r}$$

where A and A' are integration constants. Since ψ becomes zero as r increases to infinity, A' must be zero. Furthermore, A must be equal to $\frac{e}{D}$ so as to satisfy the condition that when n is very small, the potential near an ion is due to the ion alone considered as a point charge. This last condition is based on the tacit assumption that A is not a function of $\frac{1}{\lambda_D}$ when n is very small. Therefore the solution becomes

$$\psi = \frac{e}{Dr} e^{-r/\lambda_D} = \frac{e}{Dr} + \frac{e}{Dr}\left(1 - e^{-r/\lambda_D}\right).$$

If $\frac{r}{\lambda_D}$ is small, $1 - e^{-r/\lambda_D}$ is almost equal to $\frac{r}{\lambda_D}$
and so

$$\psi = \frac{e}{Dr} + \frac{e}{D\lambda_D}$$

In the absence of other ions the potential at a distance r from a given ion is given by $\frac{e}{Dr}$ therefore the second term on the right hand side must be due to the oppositely charged atmosphere. Since this expression is independent of r , it may be assumed to hold when r is zero, so that the potential ψ on the ion itself due to it's surrounding atmosphere is

$$\psi = \frac{e}{D\,\lambda_D} \quad .$$

By means of this equation it is possible to ascribe a physical significance to λ_D. If the whole of the charge of the ionic atmosphere, i.e., $-Ze$ for a positive ion of atomic number Z, were placed at a distance λ_D from the given ion the potential produced at the ion would be equal to $-\dfrac{Ze}{D\,\lambda_D}$. It follows, therefore, that λ_D may be regarded as the equivalent radius of the ionic atmosphere.

Both Gross (9) and Lax (13) have discussed plasma oscillations in a static magnetic field. Gross developed his theory by obtaining a distribution function and a dispersion relation from the solutions of the Boltzmann equation. Boltzmann's equation, including the effects of temperature motion, is

$$\frac{\partial f}{\partial t} + v \cdot \nabla f + \frac{e}{m}\left(E + \frac{v \times H}{c}\right) \cdot \frac{\partial f}{\partial v} = \left.\frac{\delta f}{\delta t}\right|_{coll.}$$

where

H = static magnetic field

E = electric fields from the particles in the system and impressed electric fields.

f = distribution function $= f(x, v, t)$.

The forces acting on the particles are principally of two types:

1. Short range forces where large momentum exchanges with neutral atoms take place. This force is written as $\left.\dfrac{\delta f}{\delta t}\right|_{coll.}$

in the equation above. In low density plasmas these collision forces give rise to damping, whereas in high density plasmas, they may destroy some of the characteristic plasma properties.

2. Long-range coulomb forces coming from other charged particles in the plasma. These coulomb forces which give rise to characteristic plasma properties, depend upon the distribution function, and allow for small momentum exchanges.

Gross found from his dispersion relation

$$(\omega^2 - \omega_p^2)(\omega^2 - \omega_p^2 - c^2 \bar{K}^2) - \omega_c^2 (\omega^2 - c^2 \bar{K}^2) = 0$$

that in the limiting case of a zero magnetic field there are two types of solutions: $\omega = \omega_p$ and $\omega = (\omega_p^2 + c^2 \bar{K}^2)^{1/2}$ where $\bar{K} = \frac{2\pi}{\lambda}$ and c is the velocity of light. The first is a "plasma type" solution in which the oscillations are longitudinal. The second solution represents transverse electromagnetic waves traveling through the ionized gas. In the limit $c\bar{K} \gg \omega_p$ the effect of the presence of ionized gas is negligible and these latter waves become electromagnetic waves in free space. For non-zero magnetic fields the two types of waves are also separated in the limit

$$c\bar{K} \gg \omega_p \quad \text{and} \quad c\bar{K} \gg \omega_c \quad .$$

It is then found that two sets of waves result, one electromagnetic, having frequencies comparable to $c\bar{K}$, the other being a plasma wave at a much lower frequency. For the plasma waves $\omega^2 \simeq \omega_c^2 + \omega_p^2$; for the electromagnetic waves

$$\omega^2 \simeq c^2 \bar{K}^2 + \omega_p^2 + \frac{\omega_p^2 \omega_c^2}{c^2 \bar{K}^2}$$

where $\omega_c = \frac{eH}{mc}$ = cyclotron frequency.

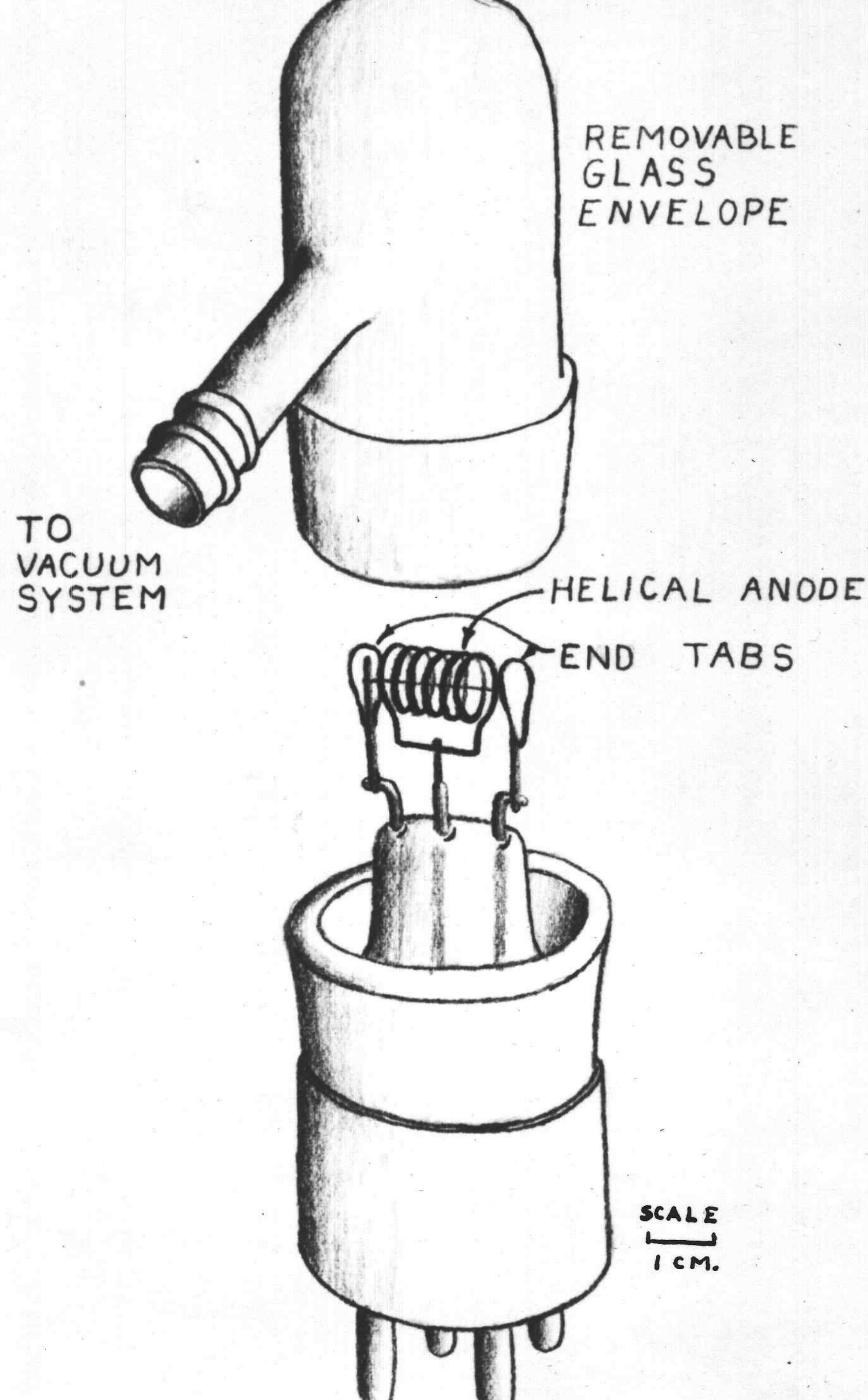
APPARATUS AND PROCEDURE

Plasma oscillations were obtained in a gas-filled cylindrical diode located between the pole pieces of an electromagnet, with the axis of the diode parallel to the magnetic field. It was found that this arrangement gave a greater number of modes of oscillations, with greater intensity, than did any other configuration.

The experimental tube, shown in Figure 1, consisted of a seven turn helical anode made by winding 24 mil molybdenum wire on a form seven millimeters in diameter, with an axial filament 22 millimeters long of 10 mil tungsten. The over-all length of the anode structure was 12 millimeters. A molybdenum disk, called an "end tab", was spot welded to each end of the filament in order to minimize the ion bombardment of the glass envelope.

Tungsten supports were used for the anode and filament. These supports were spot welded to the nickel end-seal leads. No magnetic materials were used in the ion region because of possible distortion of the magnetic field. A ground-glass seal, or joint, was used so that the tube could be taken apart in order to replace filaments.

A Distillation Products type GF-25W three stage fractionating pump and a Cenco Megavac fore pump were used to maintain partial vacuum in the tube. A Distillation Products Type VG-1A ionization gauge served to measure high vacua; a Sylvania Type R-1111 Pirani tube for low vacua. The desired pressure was maintained by allowing a small amount of gas to leak through a manually operated control valve. This control valve consisted of a pinch clamp on a section of rubber hose in which a 15 mil bronze wire was placed. The wire was



EXPERIMENTAL TUBE

FIGURE 1.

used to produce a very small orifice when the hose was pinched, thus allowing a fine control of the gas flow. The gas feeding and pumping system, shown in Figure 2, is such that the gas flow is essentially through the tube in order to sweep out vapors and gases which may be produced by arcs within it.

A Cenco No. 79,650 electromagnet, operated from a 54 volt storage battery, was used for producing the magnetic field.

The receiver most frequently used for detecting electromagnetic radiations consisted of a dipole crystal detector constructed from a 1N26 crystal cartridge. This detector, shown in Figure 5, was located near the oscillator tube. The output from the detector was amplified by means of a three section vacuum tube amplifier having an over-all band width of two megacycles and low frequency characteristics such as to respond to the 15 cycle per second repetition frequency of the square wave pulser used to supply the plate voltage. The output of the amplifier, which was applied to an oscilloscope synchronized with the pulser, was thus a square wave having an amplitude proportional to that of the radio-frequency pulses.

The first section of the amplifier was a dual unit which provided a channel for each of two detectors. It was located close to the detectors in order to minimize the capacitance of the input system and to make it possible to switch quickly from one detector to another. This dual unit is later referred to as the pre-amplifier. Each of these channels had a voltage gain of either 20 or 400.

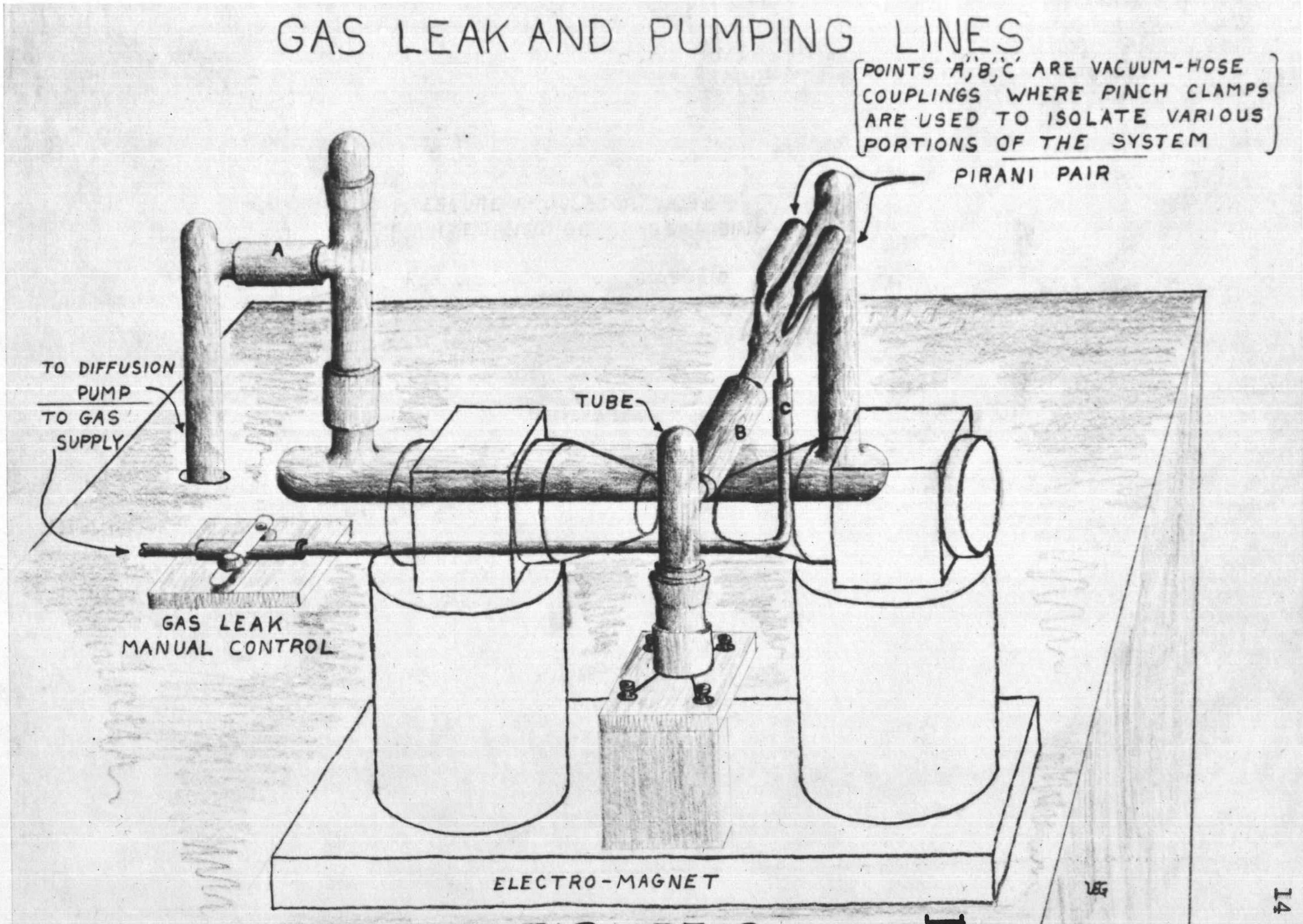

GAS LEAK AND PUMPING LINES
POINTS 'A', 'B', 'C' ARE VACUUM-HOSE COUPLINGS WHERE PINCH CLAMPS ARE USED TO ISOLATE VARIOUS PORTIONS OF THE SYSTEM
PIRANI PAIR
A
B
C
TUBE
TO DIFFUSION PUMP
TO GAS SUPPLY
GAS LEAK MANUAL CONTROL
ELECTRO-MAGNET
1"
SCALE

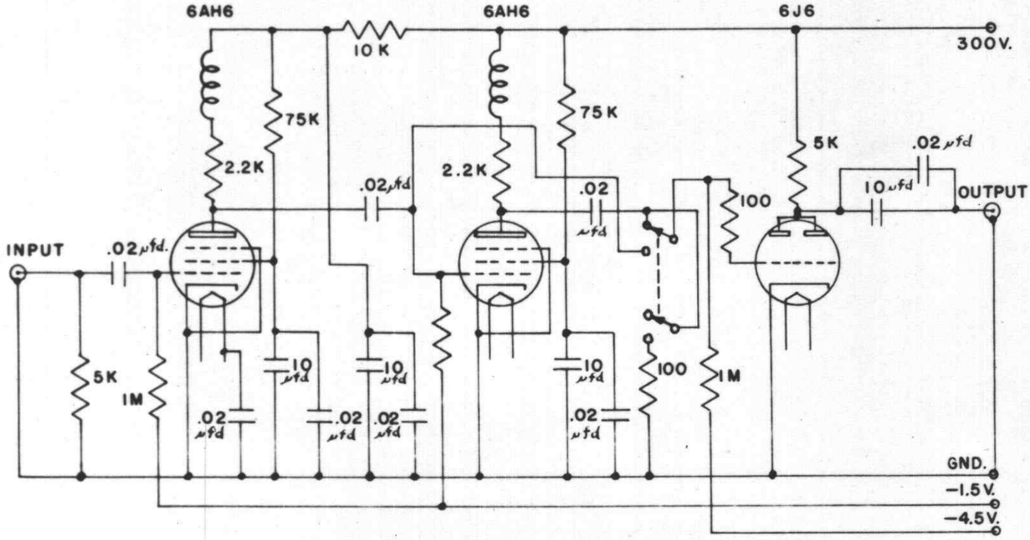
FIGURE 2

The second section of the amplifier was located near the oscilloscope. The gain of this second, or intermediate amplifier, was continuously variable between 2 and 400. The third section consisted of the oscilloscope amplifier, having a gain continuously variable between 1 and 100. Thus the gain of all three sections was continuously variable between 40 and 1.6×10^7 and was calibrated over this range. Circuits for the first two sections of the amplifier are shown in Figures (3) and (4) respectively.

An interferometer was used to measure the wave length of the electromagnetic radiations produced by the plasma oscillations. This consisted of a 14 inch by 16 inch horizontal aluminum plate movable vertically above the oscillator tube by means of a motor driven drum and cable. The movement of the metal plate was relayed to the control console by means of a selsyn circuit and indicated on a system of dials.

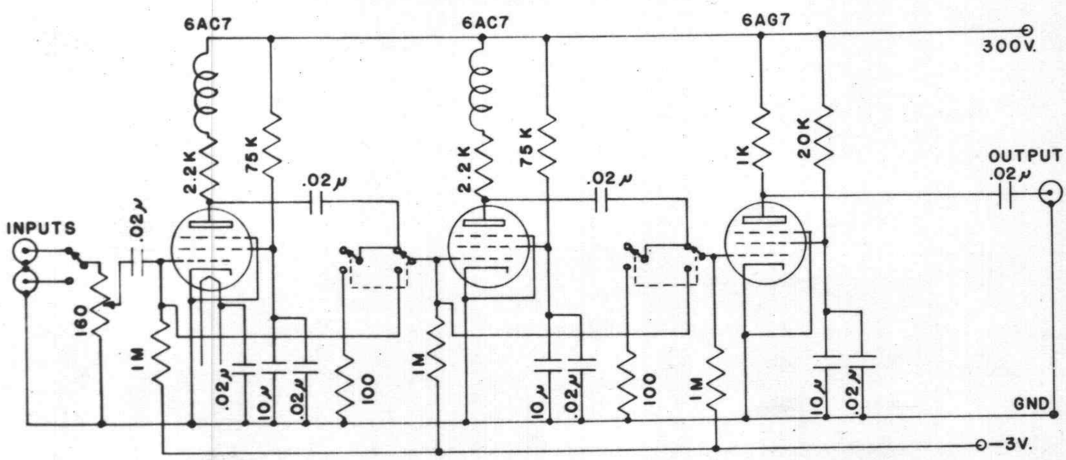
The standing waves set up at the detector by the combination of radiation directly from the tube to the detector, with that reflected from the interferometer plate, caused the output of the detector to pass through maxima and minima. Wave length measurements were made in terms of the travel of the metal plate.

The plate potential was applied in pulses at a repetition frequency of 15 cycles per second. The pulse height could be varied continuously from 0 to 1200 volts; the length from 120 to 1,000 microseconds. Pulse voltages were used in order to minimize filament bombardment and to make it possible to use alternating current amplifiers following the detector. It was found that the thermal capacity



PRE AMPLIFIER

FIGURE 3.



INTERMEDIATE AMPLIFIER

FIGURE 4.

of the filament was such that with a pulse length of 150 microseconds, at a repetition rate of 15 per second, the filament stayed at essentially constant temperature. Drawings of the pulse system and it's related monitoring equipment are shown in Figures 7, 8, 9, and 10.

Figure 11 shows the rotating-coil magnetic flux-meter used for measuring field strength. This consists of a synchronous motor, with a small coil mounted on the end of it's shaft, and a commutator for rectifying the voltage generated when the rotating coil is placed in the magnetic field being measured. The output of the coil actuates a milliammeter calibrated to read magnetic field strength in gauss.

A block diagram of the entire experimental apparatus is shown in Figure 12; a photograph in Figure 13.

The experimental tube is mounted behind the pre-amplifier and between the pole pieces of the electro-magnet, as can be seen at position (A) in Figure 13. The vacuum system, including the Pirani gauge, is beneath and behind the electro-magnet. On the console table at (B), the two oscilloscopes, monitoring instruments, and control mechanisms are located. This console was designed and built for easy access to all control devices since rapid manipulation of the controls was necessary to maintain the relatively unstable oscillations in the gas plasma. Since the operator required both hands in order to operate the equipment on top of the table, the interferometer travel control was manipulated with the feet. This foot pedal control is located below the table. Above the oscilloscopes is the intermediate amplifier, filament meter, and manual gas leak control. To

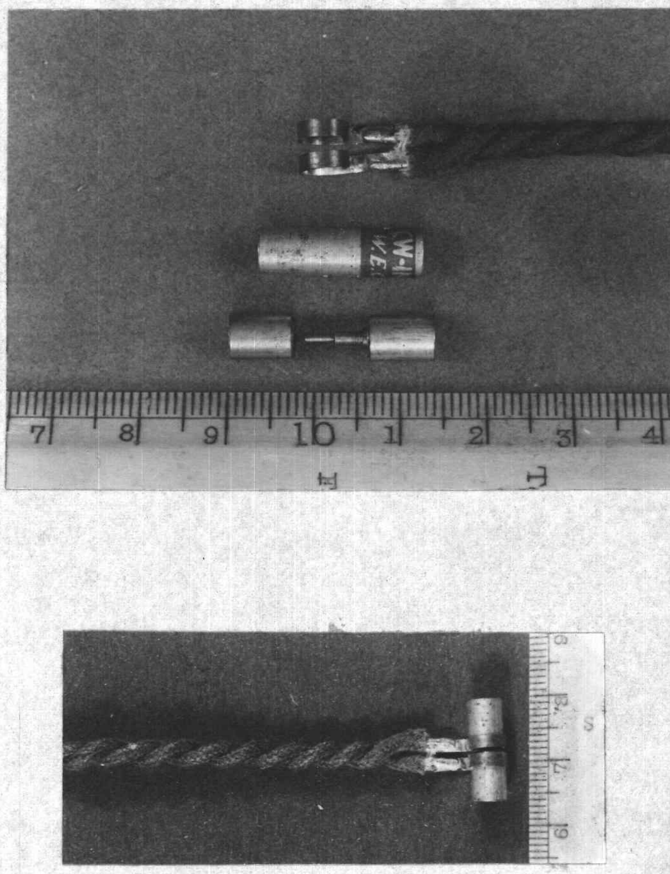


FIGURE 5

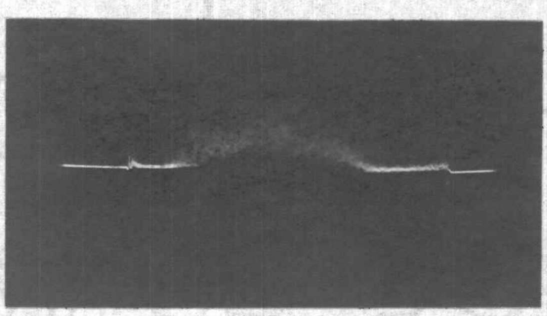
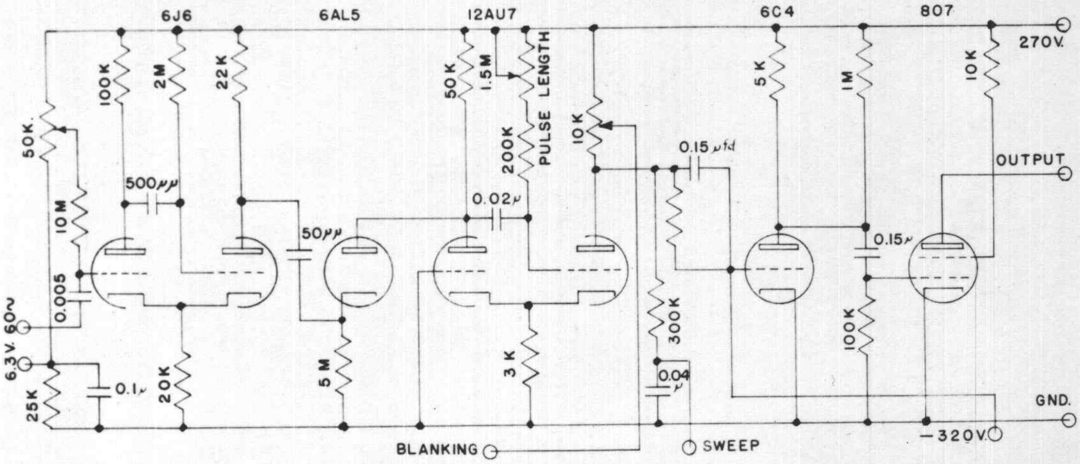
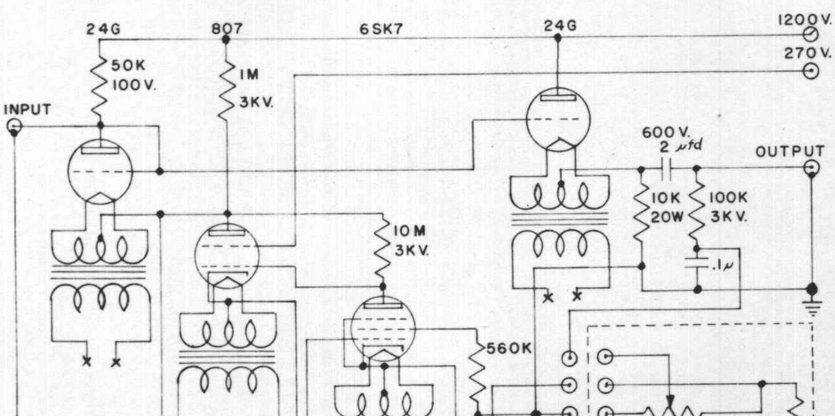


FIGURE 6



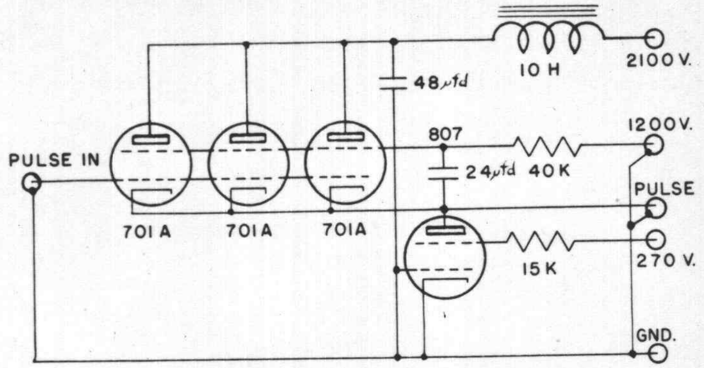
PULSE GENERATOR

FIGURE 7.



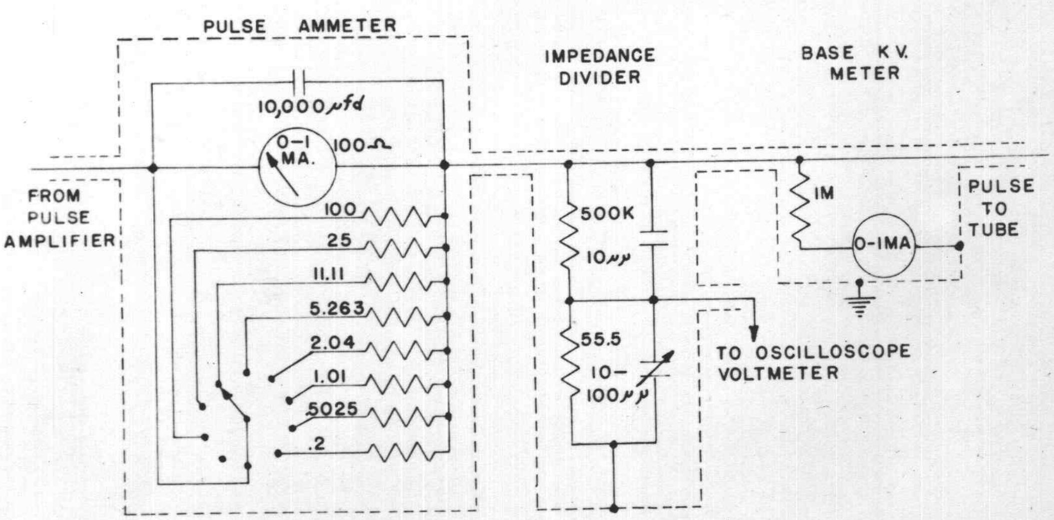
PULSE DRIVER

FIGURE 8.



PULSE POWER AMPLIFIER

FIGURE 9.



MONITORING EQUIPMENT

FIGURE 10.

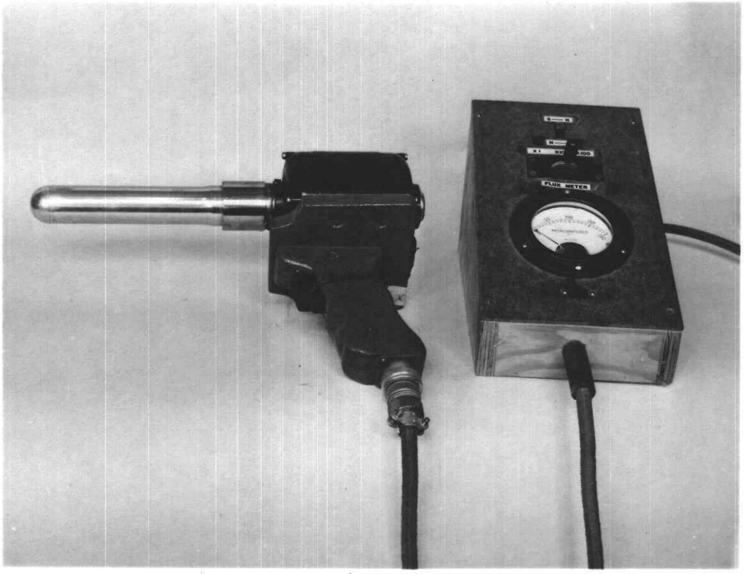


FIGURE 11

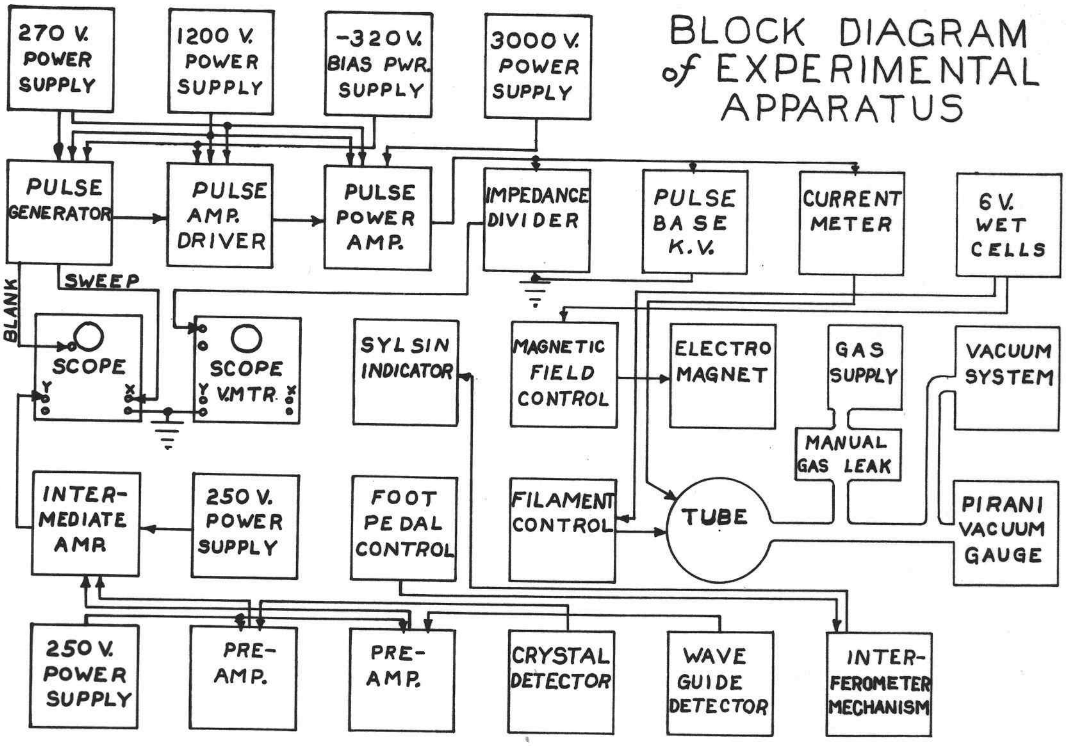


FIGURE 12

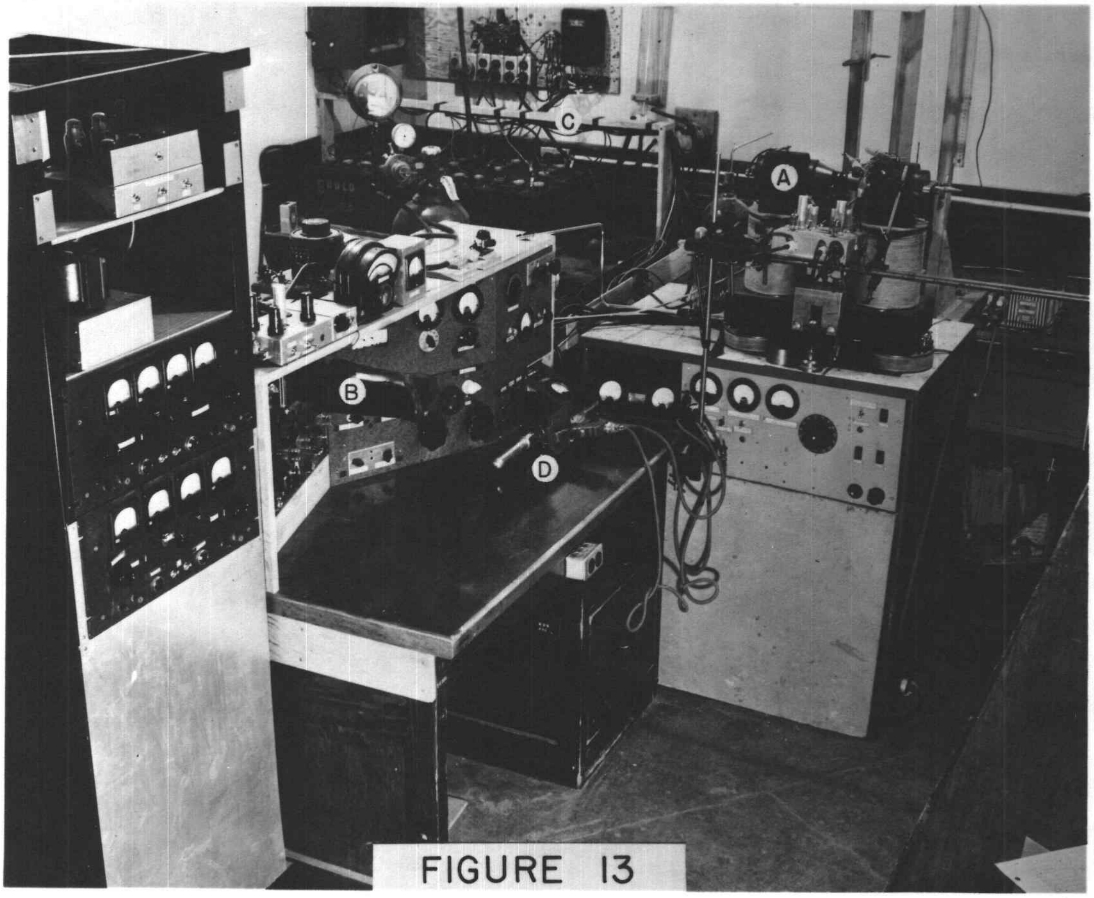


FIGURE 13

the left of the console can be seen a rack which holds the power supplies and the pulse power amplifier. On the table, at position (D), is shown the rotating coil magnetic flux-meter. The direct current supply for the tube filament, pre-amplifier filaments, and magnetic field coils is a battery of automobile lead cells shown at position (C) in Figure 13.

Not shown in the photograph are the pulse generator and pulse driver, which are located behind the control console, and the interferometer plate, which is above the experimental tube and out of the photograph.

In operating this equipment normal precautions pertaining to high voltage and time delays for the diffusion pump were observed. After the power supplies, magnetic field and filament current were turned on, the pressure in the experimental tube was adjusted to the desired value by turning the manual gas-leak valve (Figure 12). Typical operating ranges for a tube with a 10 mil tungsten filament are:

Filament current--------5 to 7 amperes

Magnetic field----------650 to 1000 gauss

Plate potential---------100 to 1200 volts

Pressure----------------2 to 40 microns Hg.

Search for an oscillation was accomplished by varying any one parameter, excluding pressure, until a noise-like envelope displaced the oscilloscope trace upward thus indicating the existence of microwave radiation from the tube. A typical oscilloscope trace of the noise-like envelope is shown in Figure 6. The wave length of the oscillation was then measured by means of the interferometer. By changing the pressure slowly the noise-like envelope would move off the oscilloscope screen and a new one would appear, but with a different wave length.

EXPERIMENTAL RESULTS

The intent of this thesis was to determine by experimental means, the effect of pressure on the wave length of plasma oscillations in argon and nitrogen. Some data were also taken in air.

It was found that with any of these gases a plot of wave length as a function of pressure, on linear graph paper, gave a curve similar to a rectangular hyperbola. Some curve fitting was done and it was determined that the experimental curves are of three possible types, namely:

$$y = \frac{1}{a+bx} \quad , \quad y = \frac{x}{a+bx}$$

$$\text{or} \quad y = c x^{d}$$

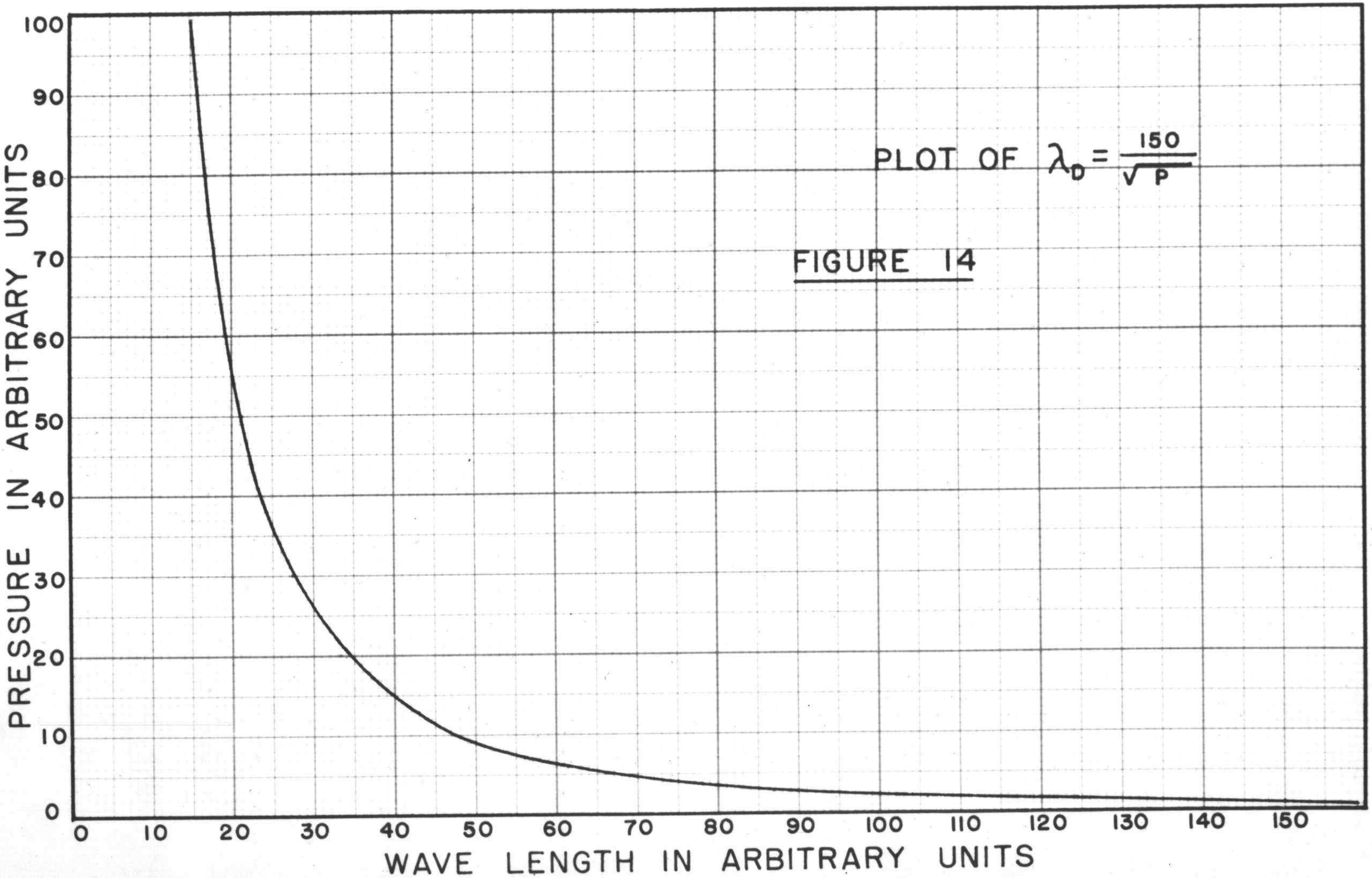
where

$$a < 0 \qquad c > 0$$

$$b > 0 \qquad d < 0$$

Wave length measurements were not taken for very low or very high pressures because of the increased instability of the oscillations in those regions. The exact position of the asymptotes of the experimental curve were, therefore, not obtained. However, if the asymptotes are considered as being the x & y axes, the general equation of the experimental curves would be of the form $y = cx^{\alpha}$. The equation $\lambda_D = \left(\frac{KT}{8\pi n e^2}\right)^{1/2}$ which was given earlier, is of this general form. By assuming an electron temperature of 10^3 degrees, and that pressure is proportional to electron density n, the Debye equation will reduce to $\lambda_D \simeq \frac{150}{P^{1/2}}$, where P is the pressure. The plot of this equation, shown on Figure 14, has a shape similar to the experimental curves on Figures 15, 16, 17 and 18. The experimental curves, therefore, would seem to have an empirical equation similar to the Debye equation. This is not surprising since the Debye equation gives the limiting wave length of the plasma oscillations for a given electron temperature T and electron density n.

An increase in filament current, which would cause an increase in electron density, should, according to both Tonk's and Langmuir's equation and the Debye length equation, decrease the wave length of the plasma oscillations. This effect was shown experimentally by two methods. The first, described in the last section, gave the curves shown in Figures 16 and 17 for argon and nitrogen respectively. Figure 15 shows a curve for air. It is seen that the trend of the curves is the same for all the gases used, but that some gases gave fewer modes of oscillation. It should also be noted that the oscillations were not continuously variable along the curves but that there exist certain discrete oscillations which occur only when the correct combination of parameters is obtained. These discrete oscillations


PLOT OF $\lambda_D = \frac{150}{\sqrt{P}}$
FIGURE 14
PRESSURE IN ARBITRARY UNITS
WAVE LENGTH IN ARBITRARY UNITS
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150

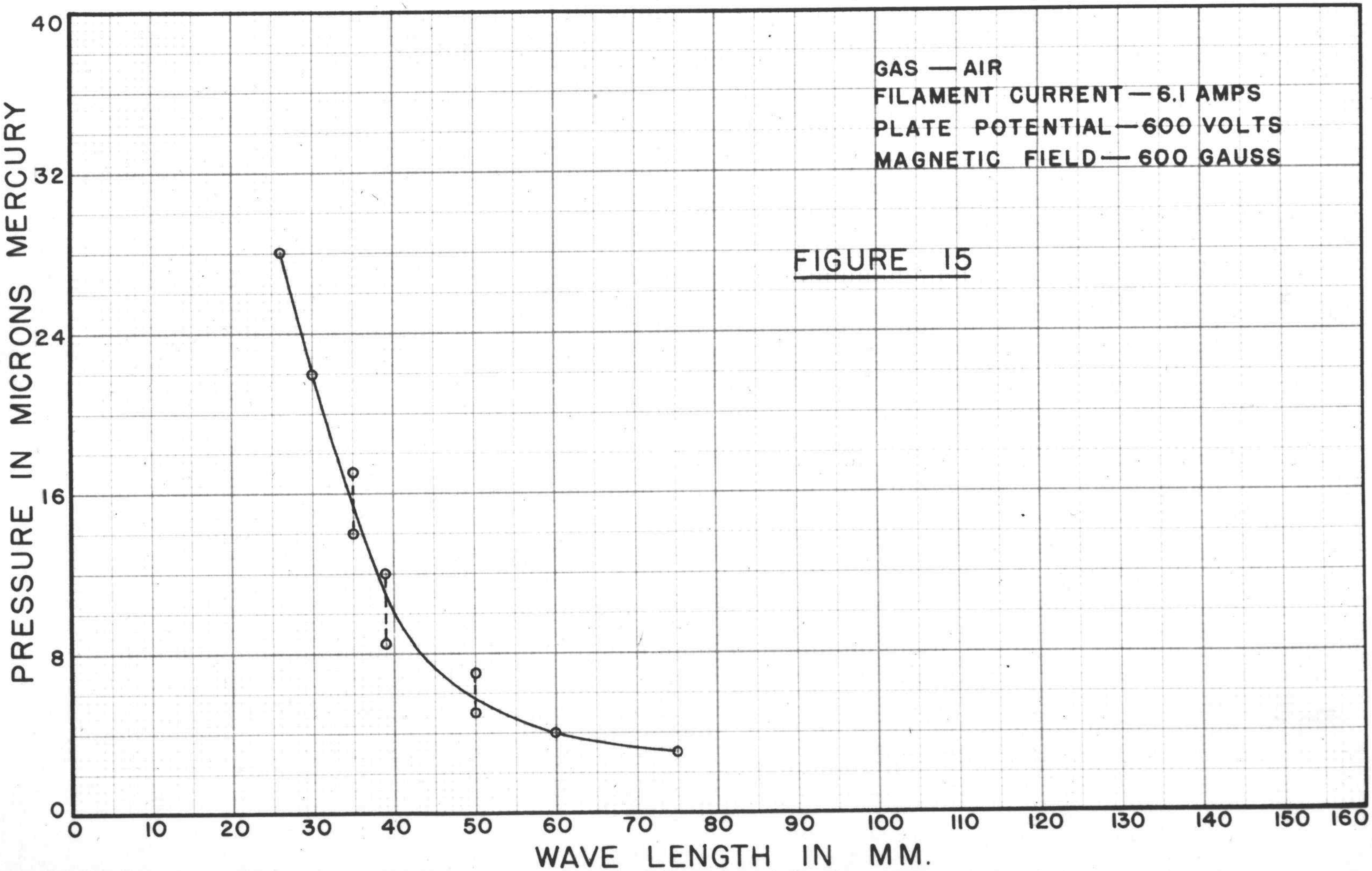
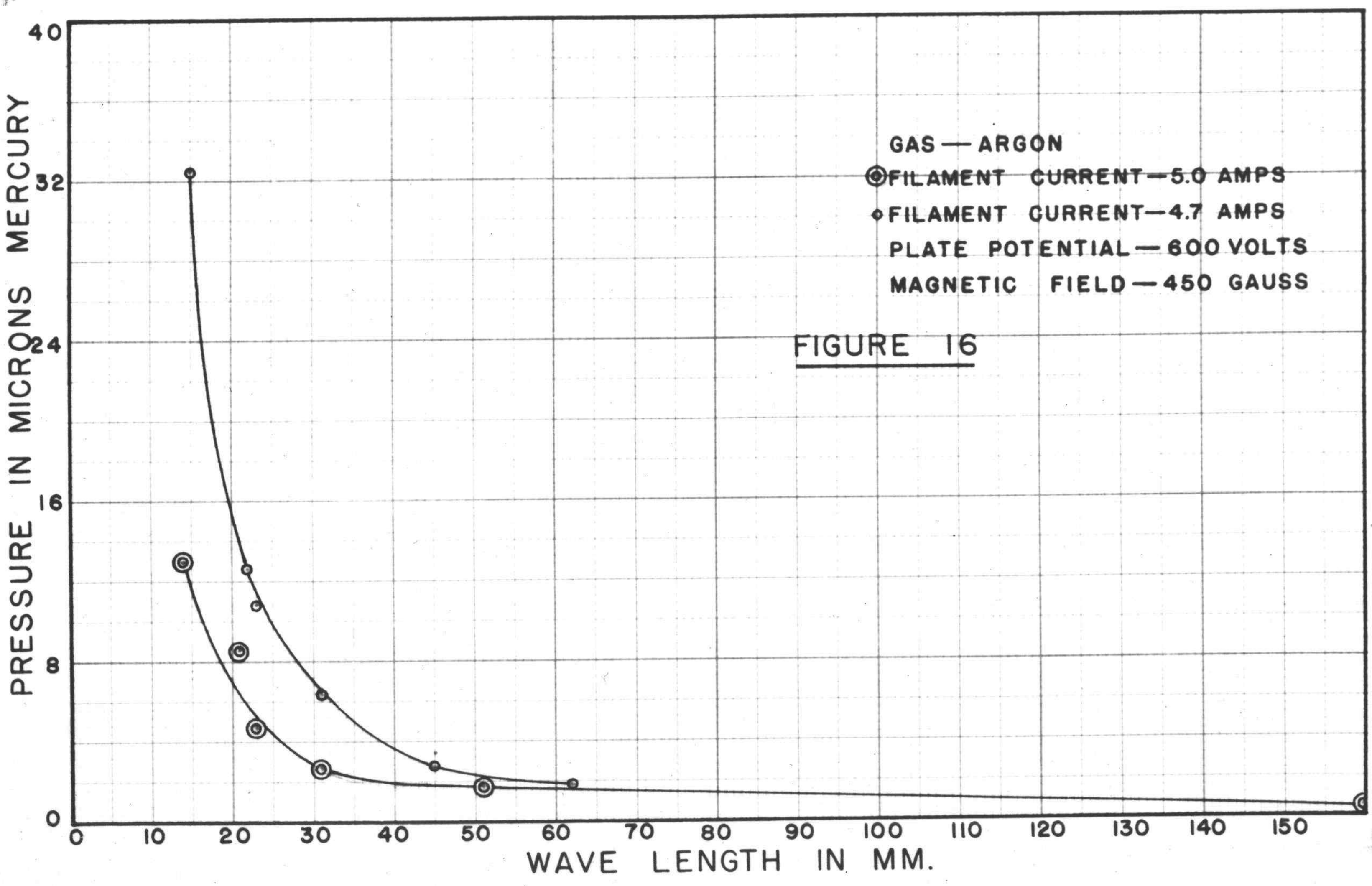

GAS — AIR
FILAMENT CURRENT — 6.1 AMPS
PLATE POTENTIAL — 600 VOLTS
MAGNETIC FIELD — 600 GAUSS
PRESSURE IN MICRONS MERCURY
0
8
16
24
32
40
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
WAVE LENGTH IN MM.

FIGURE 15


GAS — ARGON
FILAMENT CURRENT — 5.0 AMPS
FILAMENT CURRENT — 4.7 AMPS
PLATE POTENTIAL — 600 VOLTS
MAGNETIC FIELD — 450 GAUSS
FIGURE 16
PRESSURE IN MICRONS MERCURY
0
8
16
24
32
40
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
WAVE LENGTH IN MM.

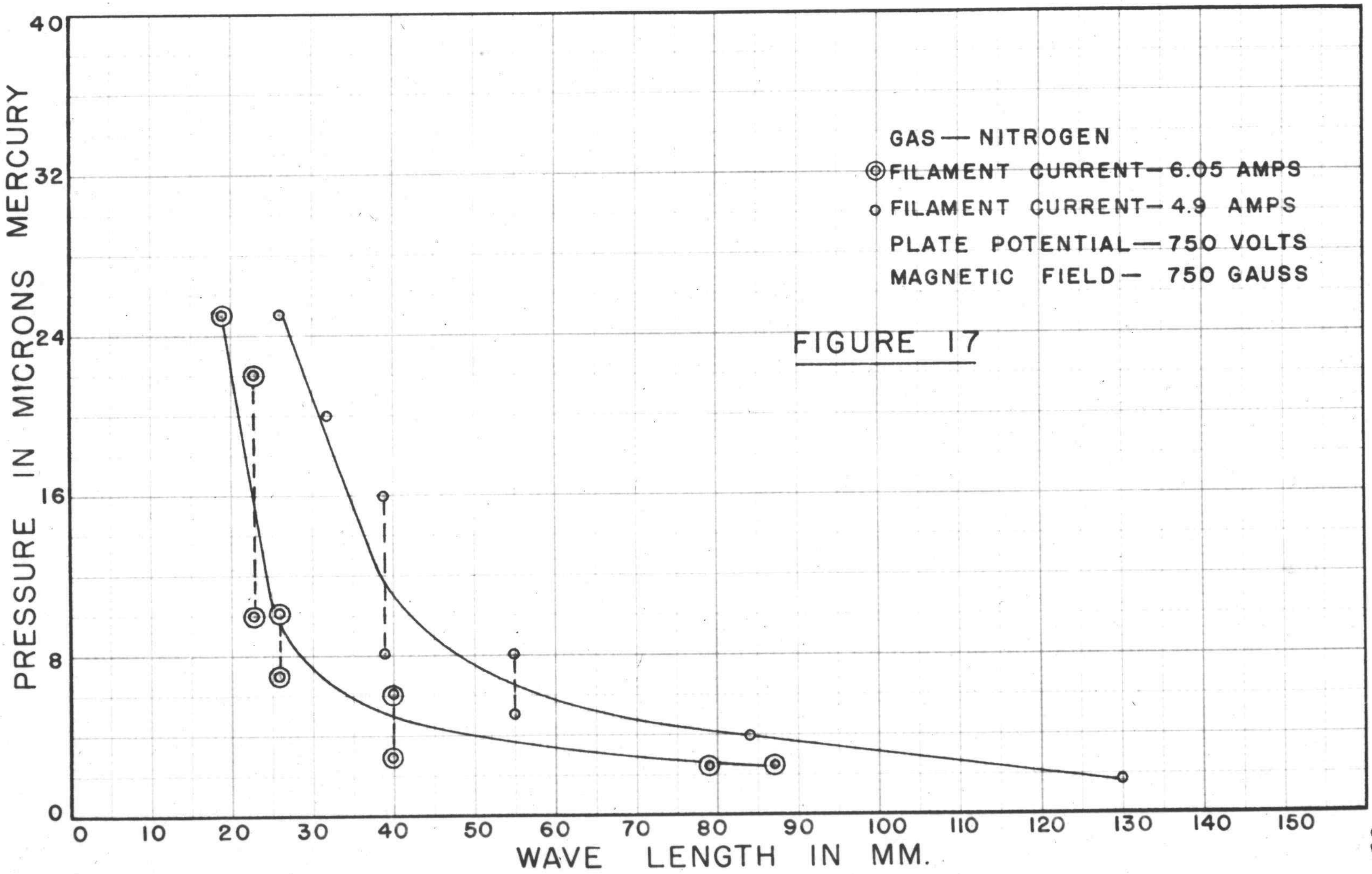

GAS — NITROGEN
FILAMENT CURRENT — 6.05 AMPS
FILAMENT CURRENT — 4.9 AMPS
PLATE POTENTIAL — 750 VOLTS
MAGNETIC FIELD — 750 GAUSS
PRESSURE IN MICRONS MERCURY
WAVE LENGTH IN MM.
0
8
16
24
32
40
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150

FIGURE 17

sometimes persist over a range of pressures. This effect is indicated on the curves by dotted lines between two pressure readings at the specific wave length.

The second method for obtaining the curve of wave length as a function of pressure, as shown in Figure 18, involved setting all parameters except filament current and then varying this current between zero and that value which caused arcing in the tube. When this was done, a number of discrete oscillations were found and their wave lengths measured. The pressure was then adjusted to a new setting and a new group of wave lengths measured. By plotting these points on linear graph paper, and indicating their respective filament currents, it was possible to draw curves connecting corresponding filament currents thus giving the curves of Figure 18.

As was described earlier, the pulse length was made short as possible in order to maintain a reasonably constant filament emission current during the period of experimental runs. Had this not been done, the destruction of the filament would have been great enough to gradually decrease the electron density in the plasma during the experiment, thus slowly shifting the curve to the long wave length side. Despite these precautionary measures, the filament destruction did cause some trouble; therefore no exact comparison can be made among the numerical values of the filament currents.

It was noted during the experiments that the intensity of oscillations, the number of discrete oscillations, and the displacement of the curves were critically dependent, in some way, on both

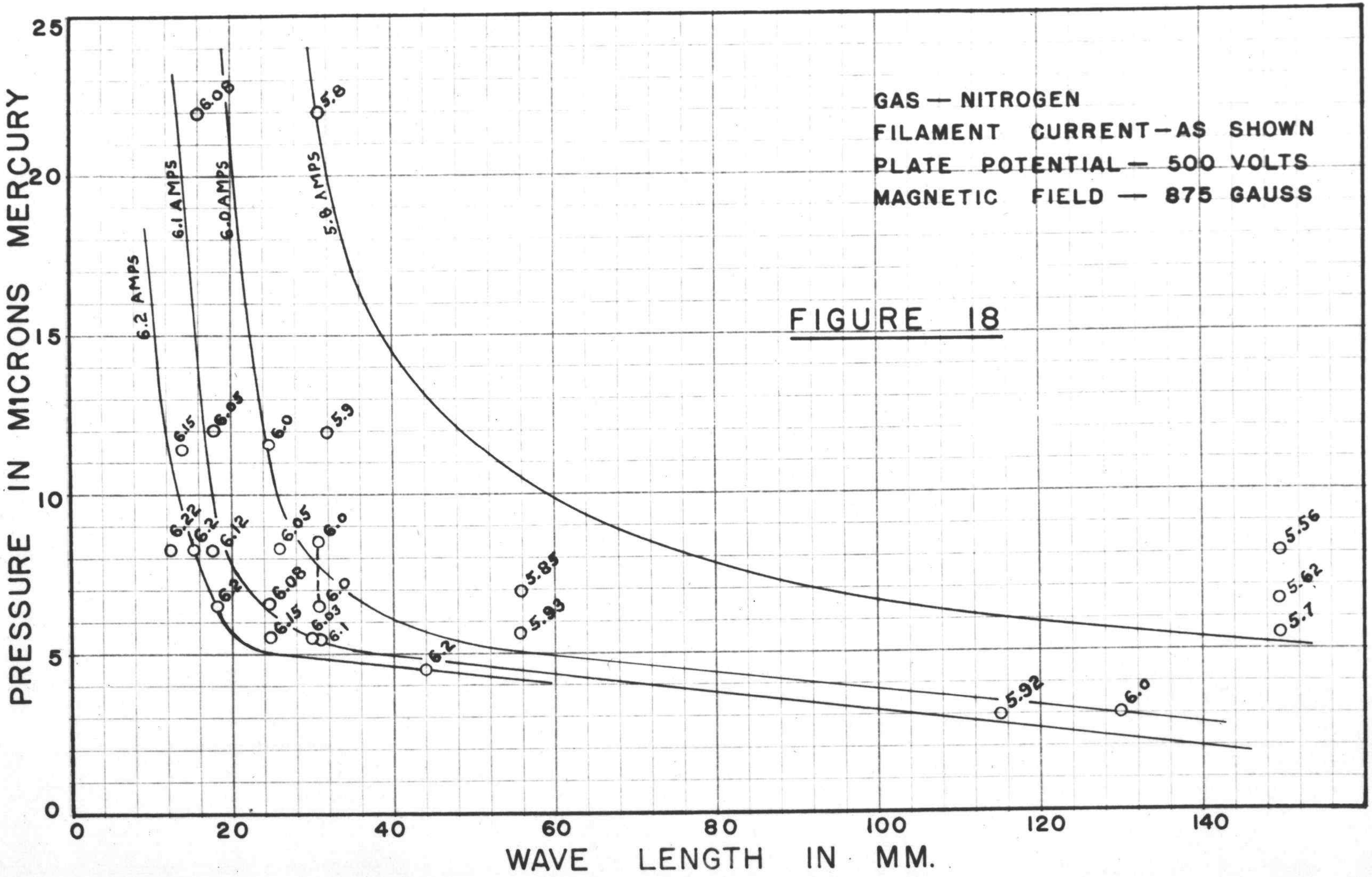

GAS — NITROGEN
FILAMENT CURRENT — AS SHOWN
PLATE POTENTIAL — 500 VOLTS
MAGNETIC FIELD — 875 GAUSS
PRESSURE IN MICRONS MERCURY
WAVE LENGTH IN MM.
6.2 AMPS
6.1 AMPS
6.0 AMPS
5.8 AMPS

FIGURE 18

plate potential and magnetic field. These phenomena were not explored.

As shown by the curves of Figures 15, 16, 17 and 18 wave lengths of plasma oscillations have been shown to be functions of gas pressure. This is consistent with the work of Tonk and Langmuir (22) on the assumption that plasma electron density is a function of gas pressure. A lower limit of wave length of plasma oscillation is also indicated by the curves in qualitative agreement with the Debye length equation.

No dependable evidence that the wave length of these oscillations differ among the gases has been found. Plasma oscillations in a magnetic field are obtained only for certain combinations of the operating parameters, and have been found to be critically dependent upon filament current. Since filaments waste away rapidly because of ion bombardment quantitative comparisons between the wave length vs. pressure curves for the two gases has not been found possible. Perhaps a first order dependence of wave length on the mass of the gas atom should not be expected since the oscillations occur in the electron gas while the atoms remain essentialy stationary.

Data of the type presented in this thesis are not found in the literature on plasma oscillations nor has adequate theory for the observed phenomena been developed. Such theory would be beyond the scope of a masters thesis and, because of the complicated nature of gaseous arcs and plamsa, will undoubtedly require a great deal more work.

BIBLIOGRAPHY

1. Bailey, V. A. The Growth of Circularly Polarized Waves in the Sun's Atmosphere and Their Escape Into Space. Phys. Rev. 78:428. 1950.

2. Bohm, D. and E. P. Gross. Theory of Plasma Oscillations. Phys. Rev. 75:1851. 1949.

3. Bohm, D. and E. P. Gross. Theory of Plasma Oscillations. Phys. Rev. 75:1864. 1949.

4. Bohm, D. and E. P. Gross. Effects of Plasma Boundaries in Plasma Oscillations. Phys. Rev. 79:992. 1950.

5. Brown, Sanborn C. and A. D. MacDonald. Limits for the Diffusion Theory of High Frequency Gas Discharge Breakdown. Phys. Rev. 76:1629. 1949.

6. Chapman and Cowling. The Mathematical Theory of Non-uniform Gases. Macmillan.

7. Debye and Huckel. Phys. Zeits. 24:185, 305. 1923.

8. Donahue, T. and G. H. Dieke. Oscillatory Phenomena in Direct Current Glow Discharges. Phys. Rev. 81:248. 1951.

9. Gross, E. P. Plasma Oscillations in a Static Magnetic Field. Tech Report No. 39, Massachusetts Institute of Technology.

10. Guthrie and Wakerling. Characteristics of Electrical Discharges in Magnetic Fields. McGraw Hill Book Company.

11. Hartman, L. M. Theory of High Frequency Gas Discharges. Phys. Rev. 73:316. 1948.

12. Jeans. Kinetic Theory of Gases. Macmillan Book Company.

13. Lax, Benjamin; W. P. Allis, and Sanborn C. Brown. The Effect of Magnetic Field on the Breakdown of Gases at Microwave Frequencies. Technical Report No. 165, Massachusetts Institute of Technology.

14. Loeb. Kinetic Theory of Gases. McGraw Hill Book Company.

15. Margenau, H. and L. M. Hartman. Theory of High Frequency Gas Discharges. Phys. Rev. 73:309. 1948.

16. Margenau, H. Theory of High Frequency Gas Discharges. Phys. Rev. 73:297. 1948.

17. Margenau, H. Theory of High Frequency Gas Discharges. Phys. Rev. 73:326. 1948.

18. Merrill and Webb. Electron Scattering and Plasma Oscillations. Phys. Rev. 55:1191. 1939.

19. Mimno, R. H. The Physics of the Ionosphere. Rev. Mod. Phys. 9:1. 1937.

20. Ramo, Simon. Space Charge and Field Waves in an Electron Beam. Phys. Rev. 56:276. 1939.

21. Slater, J. C. Electrons in Perturbed Periodic Lattices. Phys. Rev. 76:1592. 1949.

22. Tonks, Lewis and Irving Langmuir. Oscillations in Ionized Gases. Phys. Rev. 33:195. 1929.