PRELIMINARY EXPERIMENTS FOR THE STUDY OF THE ABSORPTION SPECTRA OF PLASMAS

by

SINCLAIR EDWARDS BUDD

B.Sc., University of British Columbia, 1960

A THESIS SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF

M.Sc.

in the Department

of

PHYSICS

We accept this thesis as conforming to the required standard

THE UNIVERSITY OF BRITISH COLUMBIA

October, 1961

In presenting this thesis in partial fulfilment of the requirements for an advanced degree at the University of British Columbia, I agree that the Library shall make it freely available for reference and study. I further agree that permission for extensive copying of this thesis for scholarly purposes may be granted by the Head of my Department or by his representatives. It is understood that copying or publication of this thesis for financial gain shall not be allowed without my written permission.

Department of Physics

The University of British Columbia,
Vancouver 8, Canada.

Date Oct 1 1961

ABSTRACT

A Flash Unit to supply a pulsed source of continuum radiation has been constructed to provide the light required for the study of absorption spectra of plasmas. The unit which contains the plasma has been designed to produce a gas of high purity. Several transitions in the excited neon were seen in absorption. At least two have not been reported previously. A preliminary determination of transition temperatures has been made.

TABLE OF CONTENTS

ACKNOWLEDGMENT

I would like to extend my thanks to Dr. R. Nodwell whose guidance and understanding have been of immeasurable assistance to me in this work; to other members of the plasma physics group with whom discussions have been most informative; to John Turner for the time devoted to discussions of electronics and whose ability has made much of this experiment possible; to Johnny Lees for his excellent glass blowing, and to Alex Fraser and other members of the technical staff for their cooperation.

INTRODUCTION

In the recent surge of interest in plasma physics research one of the major difficulties connected with determining the properties of the plasma has been the development of suitable diagnostic techniques. Four well-defined techniques are presently in common use in plasma physics laboratories.

1. R.F. technique using microwaves
2. D.C. probes
3. Photographic techniques
4. Spectroscopic techniques

The first two of these, while providing much accurate, interesting and useful data have the major disadvantage that they introduce perturbations into the plasma, and the effect of these perturbations may mask or alter the effect which is being measured. Photographic techniques provide information about the location of the plasmas and their approximate densities, but very little detailed knowledge.

Spectroscopic techniques, used in this laboratory for observations of both emission and absorption spectra, have a decided advantage over the first two techniques mentioned in that the measurements have very little effect on the plasma itself; and over the photographic technique in that much more information other than approximate density and position can be gathered. Besides these advantages spectroscopy is capable of

giving information about the local properties of a plasma, and when combined with electronics, time resolution.

In the interpretation of the data obtained by the study of emission spectra, it is often necessary to know the relative population densities of two levels and the probability of a transition between these levels. Unfortunately in many cases these transition probabilities are not well-known and the distribution of electrons among the energy levels may depart significantly from the usually assumed Boltzmann distribution, due to presence of impurities, because of the particular excitation mechanism or because of insufficient time to reach thermal equilibrium. It is therefore desirable that experimental investigations into transition probabilities and electron densities be undertaken. Ladenberg has shown that these quantities may be determined through measurement of anomalous dispersion and absorption spectra. It is also foreseeable that, using an appropriate modern pulse technique to trigger a short duration continuum source, we might study the time evolution of the absorption spectrum of a plasma.

This thesis describes the preliminary experimental work which has been done in preparation of the study of absorption spectra of ionized gases. Namely, the construction of the background source the design of which was inspired by the work of W.R.S. Garton[1] who has improved upon the many previous attempts to achieve a high brilliance discharge with the continuum in the ultra violet.

Chapter I

THEORY

1. Introduction

As was pointed out in the introduction, considerable information about a plasma or a hot gas may be obtained by the study of its absorption spectrum. The absorption spectrum is obtained by passing light from a source of continuum radiation through the gas under investigation. The source may be a carbon arc or, as is used in this experiment, a flash discharge. Since this gas is self-luminous the spectrum may exhibit bright lines upon the darker continuum background or dark lines upon the brighter continuum background. The result depends upon whether the background radiation is respectively hotter or cooler than the gas.

These observations can be deduced quantitatively by rearranging and solving equation A14.

$$\frac{dI_{\nu_{UL}}}{ds} = N_U \nu_{UL} A_{UL} h\nu_{UL} - h\nu_{UL}\left(N_L \nu_{UL} B_{LU} - N_U \nu_{UL} B_{UL}\right) I_{\nu_{UL}}$$

Now write the first term on the right.

$$N_U \nu_{UL} A_{UL} h\nu_{UL} = \left(N_L \nu_{UL} B_{LU} - N_U \nu_{UL} B_{UL}\right) \frac{A_{UL}}{B_{UL}} \frac{N_U \nu_{UL} B_{UL} h\nu_{UL}}{\left(N_L \nu_{UL} B_{LU} - N_U \nu_{UL} B_{UL}\right)} \quad (1)$$

At this point we should recall two important relationships between Einstein coefficients

$$A_{UL} = \frac{2h\nu_{UL}^3}{c^2} B_{UL} \quad (2)$$

$$B_{Lu}\, g_L = B_{uL}\, g_u \tag{3}$$

where g_i is the multiplicity of quantum state i.

Using equation 2, equation 1 becomes

$$N_u \nu_{uL} A_{uL} h\nu_{uL} = (N_L \nu_{uL} B_{Lu} - N_u \nu_{uL} B_{uL}) \frac{2h\nu_{uL}^3}{c^2} h\nu_{uL} \frac{1}{\frac{N_L \nu_{uL} B_{Lu}}{N_u \nu_{uL} B_{uL}} - 1} . \tag{4}$$

If the gas is in thermal equilibrium then

$$N_u = \frac{N}{Z} g_u e^{-\frac{E_u}{KT}}$$

where T is the temperature of the gas, N the total number of atoms present and Z the partition function of the gas; hence

$$\frac{N_L}{N_u} = \frac{g_L}{g_u} e^{-\frac{(E_L - E_u)}{KT}} .$$

From equation A6 and 3 we have

$$\frac{N_L \nu_{uL} B_{Lu}}{N_u \nu_{uL} B_{uL}} = e^{\frac{h\nu_{uL}}{KT}} . \tag{5}$$

Substituting equation 5 into equation 4, we get

$$N_u \nu_{uL} A_{uL} h\nu_{uL} = h\nu_{uL} (N_L \nu_{uL} B_{Lu} - N_u \nu_{uL} B_{uL}) \frac{2h\nu_{uL}^3}{c^2} \frac{1}{e^{\frac{h\nu_{uL}}{KT}} - 1} . \tag{6}$$

The specific intensity inside a black body at a temperature T is

$$\frac{2h\nu_{uL}^3}{c^2} \frac{1}{e^{\frac{h\nu_{uL}}{KT}} - 1} = B_{\nu_{uL}}(T) . \tag{7}$$

Define $K_{\nu_{uL}}$ by

$$K_{\nu_{uL}} = h\nu_{uL} (N_u \nu_{uL} B_{uL} - N_L \nu_{uL} B_{Lu}) . \tag{8}$$

This, from its appearance in equation 9, obviously is the absorption coefficient. Substitute equations 7 and 8 into equation 6, and use the resulting expression to transform equation A14 into

$$\frac{dI_{\nu_{ul}}}{ds} = K_{\nu_{ul}} \left(B_{\nu_{ul}}(T) - I_{\nu_{ul}} \right), \tag{9}$$

We now solve this equation under circumstances applicable to the present experiment. In Cartesian coordinates the equation of transfer is

$$\left(l \frac{\partial}{\partial x} + m \frac{\partial}{\partial y} + n \frac{\partial}{\partial z} \right) I_{\nu_{ul}} = K_{\nu_{ul}} \left(B_{\nu_{ul}}(T) - I_{\nu_{ul}} \right)$$

where (l, m, n) are the direction cosines of the path of integration. We choose to integrate along the y-axis, the equation becoming

$$\frac{\partial I_{\nu_{ul}}}{\partial y} = K_{\nu_{ul}} \left(B_{\nu_{ul}}(T) - I_{\nu_{ul}} \right).$$

The general solution of this equation is

$$I_{\nu_{ul}} = G\, e^{-\int K_\nu \, dy} + B_\nu(T).$$

If the absorption coefficient K_ν is constant along the y-axis, that is $N_u \nu_{ul}$ and $N_l \nu_{ul}$ are constant, the solution is

$$I_{\nu_{ul}} = G\, e^{-K_\nu y} + B_{\nu_{ul}}(T).$$

Let the plasma we are considering start at the y = 0 plane and extend in the positive y direction. If there is no external source emitting radiation in the positive y direction, the intensity at y = 0, $I(0)$, in the positive direction is zero hence

$$I_\nu(y) = B_\nu(T)\left(1 - e^{-K_\nu y}\right) \qquad (10)$$

The expotential term represents self-absorption. If there is a black body of temperature T_1 radiating in the positive y direction from y = 0 then $I(o) = B(T^1)$ and the solution to the transfer equation is

$$I_\nu(y) = B_\nu(T)\left(1 - e^{-K_\nu y}\right) + B(T')\, e^{-K_\nu y} \qquad (11)$$

Equation 11 shows that I_ν at the point of observation will equal $B_\nu(T^1)$ for any frequency away from those corresponding to atomic transitions, for at these frequencies $K_\nu = 0$. We thus see that if $I_\nu > B_\nu(T')$ the line will be bright, if $I_\nu < B_\nu(T')$ the line will be dark and if $I_\nu = B_\nu(T')$ the line will be merged with the background. If the temperature of the background radiator is greater than that of the plasma the line will be seen in absorption. To show this we first note that from the monatomic behavior of B(T)

$$B(T') > B(T) \qquad T' > T$$

From equation 11 we have

$$\left(I_\nu - B_\nu(T)\right) = \left[B_\nu(T') - B_\nu(T)\right] e^{-K_\nu y}$$

but $e^{-K_\nu y}$ is restricted to (0,1) because K_ν is restricted to $(0, \infty)$. Hence if

$$T' > T \qquad I_\nu - B_\nu(T) > B_\nu(T') - B_\nu(T)$$

or

$$I_\nu > B_\nu(T')$$

Similarly, we can show that if the temperature of the black body is lower than that of the plasma, the line will appear in emission.

If $T = T^1$, it follows immediately $I = B(T^1)$, that is, there will be neither a bright line nor a dark line. It will have blended into the background.

It might seem that these results were dependent on the assumption of thermal equilibrium in the plasma since this was invoked in the derivation of equation 5. However, the plasma temperature which we have been using to characterize the emission of the plasma at the frequency corresponding to a transition between a pair of levels l and u can be a transition temperature, T_L, defined in such a way that the ratio of population between these two levels is given by

$$\frac{N_l}{N_u} = \frac{g_l}{g_u} e^{\frac{h\nu}{kT}}.$$

This temperature is different for each pair of levels and applies only to the transition occurring between those particular levels.

2. Transition Temperature

Garton[2], because of uncertainty in the temperature of his continuum source, was unable to obtain an exact value for $B(T^1)$ so he used a procedure which would at least indicate how well a common temperature could be ascribed to his plasmas.

The total energy P falling on the photographic plate per unit time is given by

$$\int I_\nu \cos\theta \, d\omega \, d\nu$$

which for an emission line becomes by equation 10

$$P = C \, B_{\nu_0}(T) \int_{LINE} \left(1 - e^{-K_\nu y}\right) d\nu \qquad (12)$$

where $B_\nu(T)$ may be taken out of the integral because it is a slowly varying function of ν, and C is a constant representing the integral over an appropriate solid angle. The value of P, measured for different lines, need only be relative. The total absorption (or equivalent breadth) of a line from a gas backed by a source of temperature T1 is

$$W = \int_{Line} \frac{I_{\nu 0} - I_\nu}{I_\nu} \, d\nu$$

now $I_\nu \approx B_\nu(T') \, e^{-K_\nu y}$ if T^1 is $\gg$ T

and $I_{\nu 0} = B_{\nu 0}(T')$ so

$$W = \int_{Line} (1 - e^{-K_\nu y}) \, d\nu$$

thus

$$P/W = C \, B_{\nu 0}(T).$$

The -1 term representing forced emission in the denominator of the Planck formula can be dropped since $e^{\frac{h\nu}{KT}} \approx 10$ for = 7000 A^o and T = 8000 ^oK, conditions typical of the plasmas we are studying. This done, we have finally

$$Ln \frac{P}{W \nu_0^3} = Const. - \frac{h\nu_0}{KT}.$$

If a plot of $Ln \frac{P}{W \nu_0^3}$ against ν_0 results in a straight line, it can be concluded that the levels corresponding to these transitions have a common transition temperature given by the reciprocal of the slope of the line.

In the present experiment a different method is used. The photographic plate is exposed to the absorption spectrum for a time t_a, that is, for the duration of the flash, after which the emission spectrum is superimposed for a time t_e. It is

possible to adjust the time t_e until neither an absorption nor an emission line is seen on the photographic plate. In an experiment one must take notice of the intermittency effect which will be pronounced with such short exposures. This is discussed more fully in Chapter III. This time, $t_e = t_d$, is called the disappearance time. Essentially the emission line fills in the absorption line. It is difficult to expose the plate for the exact time t_d so two pictures are taken with different t_e's, allowing the disappearance time to be interpolated. The relationship between the disappearance time and the transition temperature T is

$$\frac{1}{T'} - \frac{1}{T} = \frac{K}{h\nu_0}\left[Ln\, t_a - Ln(t_a + t_d)\right] \tag{13}$$

where T^1 is the black body temperature. Interpreting the transition temperature as a parameter expression the relative population densities, we have

$$\frac{N_u}{N_L} = \frac{g_u}{g_L}\,\frac{t_a}{t_a+t_d}\, e^{-\frac{h\nu_0}{KT'}} \tag{14}$$

These formulas are derived from the following considerations. Define P as the total energy entering the spectrograph slit per unit area from one line. P will be manifest as a density on the photographic plate. The exposure P is, by the definition of I_ν, given by

$$\begin{aligned} P &= \int I_\nu \cos\theta \, d\omega \, d\nu \, dt \\ &= C\int (I_\nu \, d\nu)\, dt \end{aligned} \tag{15}$$

where C allows for the geometrical integral. From equation 11 we have P_a of the flash exposure given by

$$P_a = C\,t_a\,B_{\nu_0}(T)\int_{Line}(1-e^{-K_\nu y})\,d\nu + C\,t_a\,B_{\nu_0}(T')\int_{Line}e^{-K_\nu y}\,d\nu\,, \quad (16)$$

The integral over t in equation 15 is obviously just the time exposure t_a. As before, $B_\nu(T)$ and $B_\nu(T')$ are removed from the integral and replaced by their values at the centre of the line $B_{\nu_0}(T)$ and $B_{\nu_0}(T')$ respectively. P_e incident from the emission spectrum of exposure time t_e is

$$P_e = C\,t_e\,B_{\nu_0}(T)\int_{Line}(1-e^{-K_\nu y})\,d\nu\,.$$

The total exposure is then

$$C(t_a+t_e)\,B_{\nu_0}(T)\int_{Line}(1-e^{-K_\nu y})\,d\nu + C\,t_a\,B_{\nu_0}(T')\int_{Line}e^{-K_\nu y}\,d\nu\,. \quad (17)$$

If the time t_e is equal to the disappearance time t_d then

$$P_a + P_e = C\,t_a\,B_{\nu_0}(T')\,.$$

This equation combined with equation 17 results in a relationship between the temperature and time t_d namely

$$C\,t_a\,B_{\nu_0}(T') = C(t_a+t_e)\,B_{\nu_0}(T)\int_{Line}(1-e^{-K_\nu y})\,d\nu + C\,t_a\,B_{\nu_0}(T')\int_{Line}e^{-K_\nu y}\,d\nu$$

or

$$(t_a+t_d)\,B_{\nu_0}(T) = t_a\,B_{\nu_0}(T')\,.$$

Neglecting the term for forced emission in the plasma and using Wein's law for the black body (a doubtful step), we have

$$e^{-\frac{h\nu_0}{kT}} = \frac{t_a}{t_a+t_d}\,e^{-\frac{h\nu_0}{kT'}}\,.$$

By taking logs we have equation 13.

It remains only to determine t_d. We measure on an arbitrary scale, the exposures P_1 and P_2 of a particular line (of frequency ν_{ul}) in the two different pictures mentioned above. We know from equation 11 that

$$P_1 = C(t_a + t_{e_1})\, B_{\nu_0}(T) \int_{Line}(1 - e^{-K_\nu y})\, d\nu + C\, t_a\, B_{\nu_0}(T') \int_{Line} e^{-K_\nu y}\, d\nu$$

and

$$P_2 = C(t_a + t_{e_2})\, B_{\nu_0}(T) \int_{Line}(1 - e^{-K_\nu y})\, d\nu + C\, t_a\, B_{\nu_0}(T') \int_{Line} e^{-K_\nu y}\, d\nu$$

where t_{e1} and t_{e2} are the corresponding emission exposure times. These equations are arrived at in a manner identical to that used for equation 15. With the above two equations we can solve for

$$C\, B_{\nu_0}(T) \int_{Line}(1 - e^{-K_\nu y})\, d\nu \qquad \text{and} \qquad C\, B_{\nu_0}(T') \int_{Line} e^{-K_\nu y}\, d\nu$$

enabling us to write an equation for the intensity as a function of the exposure time t_e. If we measure the background exposure P_d, we find t_d, by solving the general equation, to be

$$t_d = \frac{P_d - P_1}{P_1 - P_2}\,(t_{e_1} - t_{e_2}) + t_{e_1}\,. \qquad (17a)$$

Another determination of transition temperature may be made by exposing a plate separately to an absorption spectrum for a time t_a and to an emission spectrum for a time t_e. The exposure for the absorption line is

$$P_a = C(t_a + t_{e_1})\, B_{\nu_0}(T) \int_{Line}(1 - e^{-K_\nu y})\, d\nu + C\, t_a\, B_{\nu_0}(T') \int_{Line} e^{-K_\nu y}\, d\nu.$$

The exposure for the emission line is

$$P_e = C\, t_e\, B_{\nu_0}(T) \int_{Line}(1 - e^{-K_\nu y})\, d\nu.$$

The exposure for the continuum is

$$P_o = C\, t_a\, B_{\nu_0}(T').$$

The difference between P_o and P_a is

$$P_o - P_a = \left[C\, t_a\, B_{\nu_0}(T') - C(t_a + t_{e_1})\, B_\nu(T)\right] \int_{Line} (1 - e^{-K_\nu y})\, d\nu .$$

The ratio of the difference to P_e is given as

$$\frac{P_o - P_a}{P_e} = \frac{t_a}{t_e}\left[\frac{B_\nu(T')}{B_\nu(T)} - 1\right] - \frac{t_{e_1}}{t_e} .$$

By establishing the exposures P_o, P_a, P_e on an arbitrary scale, from the observed densities on the photographic plate (remembering the intermittency effect) and knowing the exposure time t_a t_e and t_{e_1}, we can calculate the ratio of the continuum radiancy to the plasma radiancy. If we know the continuum temperature we can find the transition temperature.

Both these methods are used in the experiment to estimate the transition temperature.

3. Relative **A** Values[3]

The measurement of the anomalous dispersion in the neighbourhood of an absorption line but outside the region of absorption combined with the measurement of the transition temperature allows us to calculate the relative transition probabilities for lines i which correspond to transitions to a common level[3]. The anomalous dispersion is given by

$$\eta(\nu) = 1 + \left(\frac{\varepsilon^2}{2\pi m}\right) \frac{F_{u_i L}}{\nu_{u_i L}^2 - \nu^2} \qquad \text{(see Korff and Breit)}^4$$

where

$$F_{u_i L} = N_L\, A_{u_i L}\, \frac{g_{u_i}}{g_L}\, \frac{mc^3}{8\pi^2 \varepsilon\, \nu_{u_i L}^2} \left(1 - e^{-\frac{h\nu_{u_i L}}{KT_i}}\right) .$$

Since we know $\eta_1(\nu)$, $\eta_2(\nu)$ ---- corresponding to the lines i,

we know $F_{u_1 L}$, $F_{u_2 L}$ ---

Then

$$\frac{A_{u_i L}}{A_{u_1 L}} = \frac{F_{u_i L}}{F_{u_1 L}} \frac{g_{u_i}}{g_{u_1}} \left(\frac{\nu_{u_1 L}}{\nu_{u_i L}}\right)^2 \frac{1 - e^{-\frac{h\nu_{u_i L}}{kT_i}}}{1 - e^{-\frac{h\nu_{u_1 L}}{kT_1}}}$$

that is, we can find all the transition probabilities with respect to that of line 1.

The absorption spectrum affords another method of determining the relative A values. From equation 11 we see that, if the black body temperature is much higher than the transition temperature and the absorption coefficient is small (conditions which certainly exist in the present experiment) the intensity is given by

$$I_{\nu_{uL}} = B_{\nu_{uL}}(T') e^{-K_{\nu_{uL}} y}$$

thus

$$\frac{1}{y} \int_{Line} Ln \frac{B_{\nu_{uL}}(T')}{I_{\nu_{uL}}} = \int_{Line} K_{\nu_{uL}} d\nu \,. \qquad (18)$$

But from equation 9

$$\int_{Line} K_{\nu_{uL}} d\nu = h\nu_{uL} (N_u B_{uL} - N_L B_{Lu})$$

since

$$\int_{Line} N_u \nu_{uL} d\nu = N_u \quad , \quad \int_{Line} N_L \nu_{uL} d\nu = N_L$$

from their respective definitions. From equations 3, 5 and 18 we have

$$\frac{1}{y} \int_{Line} Ln \frac{B_\nu(T')}{I_\nu} d\nu = \frac{c^2}{8\pi\nu_0^2} N_L A_{uL} \frac{g_u}{g_L} \left(1 - e^{-\frac{h\nu_{uL}}{kT}}\right) \qquad (19)$$

which gives us the same information as does a measurement of anomalous dispersion.

gives us yet another advantage in that it is not necessary to calculate the true intensity as Ladenberg had to, in order to determine the relative A values for transitions with a common upper level. Supposing we have measured the anomalous dispersion for several of these lines j (a measurement of the integrated absorption coefficient would serve as well) we have

$$\frac{F_{uL_j}}{F_{uL_1}} = \frac{A_{uL_j}}{A_{uL_1}} \cdot \frac{g_{L_1}}{g_{L_j}} \cdot \left(\frac{\nu_{uL_1}}{\nu_{uL_j}}\right)^2 \frac{1 - e^{-\frac{h\nu_{uL_1}}{kT_1}}}{1 - e^{-\frac{h\nu_{uL_j}}{kT_j}}}$$

but we know

$$\frac{N_{L_1}}{N_u} = \frac{g_{L_1}}{g_u} e^{\frac{h\nu_{uL_1}}{kT_1}}$$

and

$$\frac{N_{L_j}}{N_u} = \frac{g_{L_j}}{g_u} e^{\frac{h\nu_{uL_j}}{kT_j}}$$

so

$$\frac{N_{L_j}}{N_{L_1}} = \frac{g_{L_j}}{g_{L_1}} e^{\frac{h}{k}\left(\frac{\nu_{uL_j}}{T_j} - \frac{\nu_{uL_1}}{T_1}\right)}.$$

That is

$$\frac{A_{uL_j}}{A_{uL_1}} = \frac{F_{uL_j}}{F_{uL_1}} \frac{\nu_{uL_1}}{\nu_{uL_j}} \frac{B(T_j)}{B(T_1)}$$

In summary, we gain two advantages which Ladenberg did not have when we know the transition temperature. Firstly, we can calculate the relative A values for common lower level transitions when there is a high transition temperature and secondly, we can calculate the relative A values for common upper level transitions without evaluating the integral of equation 19.

4. Correlation of Electron Temperatures to Excited Level Populations[3,6].

The equilibrium distribution in the populations of the

levels of excited atoms is dependent upon the electron distribution function. This function is governed by Boltzmann's transfer equation

$$\frac{\partial f}{\partial t} + v \cdot \nabla_r f + \frac{e X}{m} \nabla_v f = \frac{\partial f}{\partial t}\Big)_{Collisions}$$

where the number of electrons n enclosed by the volume $dx\ dy\ dz$ at the point xyz and with velocity between $v_x, v_x + dv_x$, $v_y, v_y + dv_y$ and $v_3, v_3 + dv_3$ is given by

$$dn = n f(x\ y\ 3\ v_x\ v_y\ v_3)\ dx\ dy\ d3\ dv_x\ dv_y\ dv_3$$

n is the density of electrons.

If the field is in x direction only and $\frac{dn}{n}$ is a constant in space the equation reduces to

$$\frac{\partial f}{\partial t} + \frac{e X}{m} \frac{\partial f}{\partial v_x} = \frac{\partial f}{\partial t}\Big)_{collisions}.$$

On the assumption that the plasma can be modelled after a Lorentz gas, that is one where m the mass of an electron is much less than the mass M of the molecules and the density of the electrons is small as in a weakly ionized gas, the velocity distribution is nearly isotropic except for small deviations due to electric field and diffusion. The equation is solved by expanding f in spherical harmonics and equating corresponding terms. The answer depends on our approximation for $\frac{\partial f}{\partial t}\Big)_{Collisions}$.

Margenau, considering only elastic collisions and a constant electron mean free path, found that for small high frequency fields of amplitude x_0 and angular frequency W in which ionization can be neglected, the distribution function is Maxwellian with $T_e = T_{gas} + M e^2 X_0^2 / 6 K m^2 w^2$.

Though the model used was only approximate we can expect to have a distribution which is nearly Maxwellian.

Under certain general conditions, theoretical considerations show the existence of a statistical equilibrium between electrons and excited atoms and the validity of the Boltzmann law for the excited atoms. To demonstrate this, it is necessary only that the velocities of the electrons in the plasma have a near Maxwellian distribution and that the current density be very high so that collisions of the second kind between the electrons and excited atoms destroy per second approximately as many atoms as are excited by electronic collisions. That is to say, these two processes of excitation and de-excitation must predominate over those of collisions with the walls, collisions with other atoms, spontaneous radiation and radiant excitation.

With these two conditions it is shown that the ratio of the populations of two atomic levels corresponds to a statistical equilibrium at the electron temperature. At higher pressures this statistical equilibrium will be reached for lower current densities. This is a natural consequence of the decrease in the rate of diffusion to the walls of the excited atoms as the pressure is raised, and the increase in the number of slow electrons responsible for collisions of the second kind with the excited atoms, with a rise of pressure at constant current.

5. The Neon Spectrum

The lowest state of neon is the configuration $2p^6$, which gives rise to the single state ^1S_o. This configuration is very stable and a large energy is required to bring the atom into the first possible excited state $2p^5.3s$ which lies over 130,000 cms^{-1} higher. All the excited states lie in the region between 130,000 and 174,000 cms^{-1} from the normal state.

The lowest configuration of the neon ion is $2p^5$ which gives rise to an inverted ^2P state, with a doublet separation of 780 cms^{-1}. Thus the excited states of neutral neon in a first approximation can be considered to arise from the addition of an electron to the core in either the $^2P_{\frac{3}{2}}$ or $^2P_{\frac{1}{2}}$ state.

According to Shortley, the LS designation can be assigned significantly to only the following configurations, the $2p^5.3p$ and the series $2p^5.ns$. The three lowest levels of $2p^5.3s$, the first excited configuration, form the inverted ^3P state, $^3P_{210}$. The $^1P_1$ state is 1070 cms^{-1} above $^3P_0$. The $^3P_2$ and ^3P_o levels are metastable while the $^3P_1$ and $^1P_1$ levels combine with the normal state to give the ultra violet resonance lines 743 and 736 Å. The levels $^3P_{210}$ all have approximately the same population densities, even though $^3P_1$ is unstable, since at room temperature the mean energy of the neon atom is of the same order as that of the energy difference between these levels, allowing the population of the $^3P_1$ term to be replenished by collision with the metastable states $^3P_2$ and ^3P_o. The $2p^5.3p$ configuration gives rise to ten levels, ^1S_o, $^3S_1$, ^1P_o, $^3P_{o12}$,

$^1D_2$ and $^3D_{123}$. The terms of the above configuration combine to give about thirty spectral lines. In figure 1, the lines which were observed in the experiment are indicated.

Chapter II

APPARATUS

1. Introduction

The general arrangement of the equipment used for the investigations described in this thesis is illustrated in figure 2. Light from a high temperature source of continuum radiation, the flash unit, passes through a plasma generated in the plasma unit. In this experiment the plasma is created by a Radio frequency discharge but the plasma source could be replaced by other sources such as a shock wave. The light, having passed through the plasma, is photographed with a spectrograph to record the resulting absorption spectra. In one phase of the experiment it is necessary to control the relative exposure times of the plasma and flash units. This can only be accomplished with rapid shuttering of the spectrograph since the plasma unit is a continuous radiator and the flash unit a pulsed radiator. The flash unit has to be synchronized with the shutter unit. This is achieved by firing the flash unit with a pulse from the trigger unit which is tripped by the output pulse of the delay unit. This delay unit pulse is initiated by a signal from the shutter unit which occurs at a fixed time in advance of the opening of the spectrograph shutter.

2. The Flash Unit

The flash unit, to fulfill its function adequately, was constructed with many different operating characteristics.

From a preliminary experiment using neon in the plasma unit and employing the positive crater of a carbon arc for the continuum radiation with a spectral steradiancy approximating that of a 5000°K black body, it became obvious that we would require even higher spectral steradiancy. Since in the future it is hoped to apply this diagnostic technique to other plasmas at temperatures of tens of thousands degrees Kelvin it was decided to use an impulsive discharge for the source of radiation. Besides requiring the high spectral steradiancy from our source it is also advantageous to have the spectrum free of lines and bands in either absorption or emission so that absorption coefficient integrals may be easily evaluated and the spectral distribution may be compared conveniently to that of a black body.

In future experiments it is hoped to investigate with this technique, transient plasmas decaying in the order of milliseconds. To do this with good time resolution the pulse discharge should have a duration of only microseconds. However in the steady state experiment described in this thesis the short duration of the source proved to be more a nuisance than an advantage.

In order to produce a useful photographic record of the absorption spectrum resulting from the passing of the discharge light through the plasma unit, it required the superposition of at least four exposures. Two pictures, and preferably four, are required to provide sufficient data for the determination of population densities and transition probabilities.

We must thus have the flash unit output identical for at least eight discharges.

As was pointed out in the introduction to this chapter it is necessary to trigger the discharge at a precise moment. In the present experiment a jitter time of the order of twenty microseconds between the triggering pulse and the discharge in the flash tube is tolerable. However future experiments dealing with transient plasmas will require much smaller jitter times. Hence it was decided to design the triggering system with as small a jitter as possible.

In the experimental evaluation of the flash unit electronic measurements are made simultaneously with the discharge in the flash tube and for this reason it is desirable to choose a geometry for the electrical leads which has a low radiating efficiency. The choice of construction materials and design of the flash unit was made also with the purpose of assuring it a long life, of facilitating its alignment with the other units and making it easily replaced or repaired. The design of the flash unit is illustrated in figure 3. This final choice was made in an attempt to embody all the considerations mentioned above and to arrive at a compromise where conflicts existed.

In principle, the operation of the unit is very simple. The aluminum electrode E_1 cemented to the discharge tube, is connected to the copper collar C_1 4.8 cm. long, 2.7 cm. $I.D._1$, by means of eight radial screws. This copper collar is connected

to the centre of the condenser through the plane lead L_1. The aluminum electrode E_2 is attached to the copper collar C_2 by a wire gauze soldered to the collar and necked down to the electrode where it is secured by a metal strap. Collar C_2 is connected to the outside of the condenser by the plane lead L_2. Thus when the trigger pulse is applied to the trigger leads TL, the condenser current rises up through plane lead L_1, travels down the outside of the flash tube through C_1, in through the eight screws to the electrode E_1, and then down the inside of the quartz flash tube, initially under a vacuum of .1 microns to the electrode E_2, where it returns to the condenser via the wire gauze to C_2 and L_2.

The insulating plate Ip, 1.5 mm. thick, is cemented to the insulating cylinder Ic, allowing the plates L_1 and L_2 to be placed close together. Finally the light from the discharge is observed through the window W_2, while through window W_1, the unit is aligned.

In the course of designing the flash unit, primary consideration was given to achieving a uniform continuum and high temperatures. Contributing greatly to the uniformity of the discharge spectrum was the use of quartz instead of glass for the discharge tube. With a glass tube the discharge spectrum always showed the sodium D lines strongly in absorption. This occurred because sodium from decomposed glass near the walls was cooler. The quartz tube showed no strong absorption lines.

As is well-known from the work of Anderson[7], the parameter which determines to a large extent the uniformity of the continuum is the current density in the discharge channel. From his investigations it is seen that a current of twenty or thirty thousand amperes per square centimeter is necessary. The current which flows during the discharge is given by the expression

$$i(t) = \left[\frac{\mathcal{E}}{\frac{1}{LC} - \left(\frac{R}{2L}\right)^2}\right]^{\frac{1}{2}} e^{-\frac{R}{2L}t} \sin\left(\sqrt{\frac{1}{LC} - \left(\frac{R}{2L}\right)^2}\, t\right).$$

As is seen from this formula a low inductance is important for high current densities. For this reason coaxial geometry was initially considered for the flash unit. The low radiating efficiency of coaxial geometry added appeal for the choice of this form.

It is fortunate that a uniform continuum and a high temperature are products of the same conditions. An equation expressing the conservation of energy for the discharge can be written

$$\frac{dE}{dt} = i^2R - E(\tau T) f(T) - A\sigma T^4$$

where $\frac{dE}{dt}$ is the rate of change of the total energy of the tube; i^2R is the rate at which energy is added to the discharge; E(tT) is the energy of the discharge at a given time and given temperature. Since the plasma is a gas, it is an increasing function of temperature; f(T) is the fraction of total energy lost per second by mechanisms other than radiation. It is most plausible that this is an increasing function of temperature; the term $A\sigma T^4$

represents the power loss by radiation. In a steady state i.e. $\frac{dE}{dt} = 0$, we see that we would have an increase in temperature with an increase in current. From the foregoing considerations we conclude that to achieve a uniform continuum and high temperature large currents generated by the use of low inductance circuits in the leads and discharge tube, high voltages, and large capacitances are required. The condenser used was a 1.6 m.f.d. low inductance, 25 mμh, high voltage, 25 kv. manufactured by Cornell-Dubilier, model NRG 323.

The use of large currents creates a major problem. Since the currents are flowing in opposite directions in the two plates which are separated by only 1/16 inch of perspex (to keep the self-inductance low) a strong repulsive force exists between them. The magnitude of this force can be estimated by using a very simple calculation. Supposing the current is damped out in two periods we have approximately one-quarter of the stored energy dissipated in a half period. If all of this energy were converted into the kinetic energy of the plates their final velocity would be

$$V = E\sqrt{\frac{c}{8m}}$$

where E is the condenser voltage and m the mass of one plate. These plates acquire the velocity in a half period. Hence the force from $F.\Delta T = m.\Delta V$ is

$$F = \frac{E}{P}\left(\frac{m2}{c}\right)^{\frac{1}{2}} \qquad (21)$$

where P is the period.

In substituting values we have

$$F \approx 10^5 \text{ Newtons.}$$

This force would be applied to the quartz-electrode junctions if the gauze collar which absorbs the shock were not used to join the electrode E_2 to the plate P_2. This made it possible to use black wax to cement the electrode E_2 to the quartz tube. The electrode E_1 had to be cemented with epoxy because screws were used to connect the electrode to the copper cylinder, enabling easy alignment.

Even with the gauze a small force is exerted on the tube. If the tube is glass this force tends to shatter it after a few firings since the strength of the glass is reduced by crazing caused by the discharge. It was found that quartz did not craze as readily as glass allowing the tube to withstand many more discharges. This is another reason for the choice of quartz over glass in the construction of the discharge tube.

The high voltages employed necessitate special insulation precautions. Figure 4a shows the details of the electrodes E_1 and E_2. The electrodes are grooved so that the quartz-electrode junctions inside the vacuum of the discharge tube occur recessed in the electrodes, a region of low electric field. This is in accordance with the findings of Kofoid[8].

The hollow cylinder I_c of perspex allows the discharge tube to be easily withdrawn and replaced simply by undoing the gauze strap and the screws. The cylinder extends 3 cms. on either

side of the insulating plate and by extending the effective path in air between the copper plates, breakdown is prevented. The increase in inductance from 3.6 mμh. with the return conductor flush with the discharge tube to 12 mμh. with it removed by .8 cm. was considered worth the sacrifice for the simplification of the removal and insulating problems.

In order to have the discharge spectrum reproducible to the demanded degree, five different arrangements were tried. The first trial (figure 4a) had the windows placed flush with the electrode. They became opaque after two shots because of deposition resulting in fogging and ebulation resulting in pitting. It appeared that this deposit was from the electrodes and walls since one part could be dissolved from the windows with nitric acid and another part with hydrofluric acid. The deposition was examined by constructing a pinhole camera (figure 4b) at one end of the discharge tube. The material was deposited lightly over the whole window except for a dense ring centered on the axis of the tube. This ring corresponded with the optical image of the opposite electrode. The ebulation was confined to a circle in the centre of the window. While the pinhole camera was attached it was decided to measure the directional dependence of the light output of the discharge by using sensitized paper. It was found to be essentially constant for at least 10^{o} off the axis.

These findings in mind, a second try was made (figure 4c) with a glass baffle of such size that, placed near one

electrode, part of the nearby window could not see the far electrode. This failed because there was diffusion and scattering of electrode material.

In the next attempt a window was moved from the main discharge path by placing it on the end of a branch of a wye (figure 4d). After one shot, the window became contaminated due to the condensation of the discharge debris. From this observation a mechanism by which the main discharge tube keeps clean is suggested. It appears that the discharge evaporates the material condensed during the latter part of the previous discharge. At present experiments are being concluded to develop a window system which exploits this self-cleaning process.

In the fourth design it was hoped to make use of electrostatic deflection. One window was moved away from the end of the discharge tube and electrode by adding a section of glass tubing (figure 4e). Two metallic deflection plates D, length L_1, were placed diametrically opposite on the outside of the extension thus separating them by a distance $S \approx 1$ cm. They had a voltage placed across them equal to that of the condenser potential. Assuming that a particle would convert all of its potential energy to kinetic energy, that is

$$K.E. = qV$$

where V is condenser voltage.

By the equation of motion, and assuming plane parallel electrodes

$$F = qE = \frac{qV}{S} = ma$$

where E is the electrostatic field inside the extension tube.

Hence the time required for a particle to travel from one side of the extension to the other is

$$t_1 = S\sqrt{\frac{2}{V\, e/m}} \quad .$$

The time to go from one end of the extension to the other, a distance L is

$$t_2 = \frac{L}{\sqrt{2}}\sqrt{\frac{1}{V\, e/m}} \quad .$$

If these times were equal no particle would reach the window. That is if

$$L = 2S.$$

When such dimensions were used no improvement was noticed. Thus this suggested the discharge was in the form of a neutral plasma since the particles could not have recombined to form neutral molecules in the short transit time.

The fifth design (figure 4f) and the one used in the present experiment was a partial success. As in trial four, extensions are used but this time, to keep the windows clean, a glass tube at one end of which there is a constriction in the form of a slit, was placed inside each window extension with the slit towards the electrodes. This arrangement kept the windows clean for twelve discharges. The length of the extension, 3 cms. is determined by a compromise between two advantages. The further away the windows are from the discharge the cleaner they stay because they subtend a smaller solid angle to the discharge; however the nearer the windows are to the slit the smaller the f number they allow for the system. This design does not take advantage of the large diameter of the discharge

tube which could be used to present a source extended in area for the experiment.

In order to achieve satisfactory triggering two entirely different methods were tried. The first was an attempt to use ultra violet light recognizing the fact that if it worked, it would be very safe as there would be no electrical connections between the triggering system and the high voltage of the condenser. Light from a triggered spark passed through a quartz window and fell on the negative aluminum electrode E_1 (figure 5a). For this to trigger the discharge the voltage of the condenser had to be set too near the breakdown valve, causing spurious discharges.

This method was then abandoned in favour of introducing trigger electrodes directly into the discharge tube as shown in figure 5b. Initially one trigger electrode was used allowing it to arc to the discharge electrode E_1. This would only trigger when E_1 was negative with respect to E_2, regardless of the polarity of the 32 kv. trigger pulse. Hence it was concluded that the electrons emitted from the trigger discharge were necessary to initiate the flash discharge. (It was not the photo-electric electrons from E_1, since both polarities of the trigger pulse do not work equally well). For more reliable triggering it was necessary to introduce another trigger electrode running it into the space between E_1 and E_2 and to have the arc occur in this space where the electric field would accelerate the electron towards the far electrode. This arrangement is used in

the final design. It is necessary however to keep these trigger electrodes as near to the cathode E_1 as possible so that when they are immersed in the resulting discharge their potential will not rise too high.

Upon completion of the flash unit determinations of several of its operating characteristics were made. The time derivative of the current as a function of time is shown in figure 6a. This was photographed from an oscilloscope display at a sweep speed of one microsecond per centimeter of the voltage induced in a search coil placed near the discharge. This voltage is given by

$$V = M \frac{di}{dt}$$

where M is the mutual inductance between the coil and the discharge circuit. The observed waveform corresponds accurately to the calculated one in A17. This shows that the model used to derive equation A15 is quite good. Using the method outlined in the appendix and the observed values of $P = 19.6 \pm .09 \times 10^{-6}$ seconds and $LD = 1.52 \pm .07$ we find

$$\eta = 3.34 \times 10^{6} \pm .15 \text{ seconds}$$
$$L = 56 \pm 5.6 \times 10^{-9} \text{ henries}$$
$$R = .087 \pm .007 \text{ ohms.}$$

The value of the period in the calculation must be taken from two successive zeros and not from the time zero and the first zero as half a period since there is a phase angle (equation A17) to be considered. Using the values of L and R the current is given to 30% by

$$i = 82{,}700 \times 10^3 \, e^{-7.73 \times 10^5 t} \sin 3.24 \times 10^6 t$$

By observation $\frac{di}{dt} = 0$ at $t = .6 \times 10^6$ seconds.
Hence the maximum current is 48,700 amperes. From these values we see the current density in the discharge is $75 \pm 11 \times 10^3$ amps./ cm.^{2}. This is well above the threshold for continuum radiation.

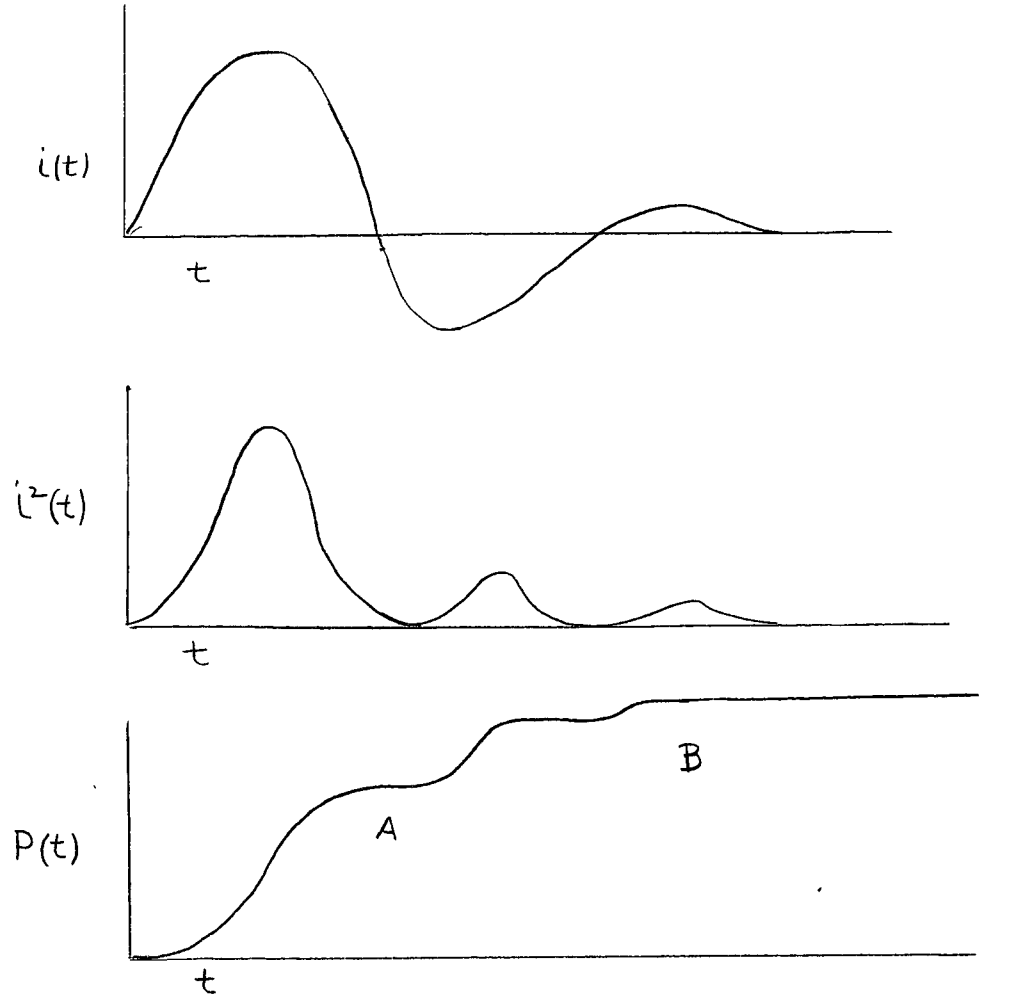
The change in output spectrum as a function of the condenser voltage was examined. At low voltages or equivalently low current densities there are lines and bands, but as the voltage reaches 15 kv. the continuum becomes quite uniform except for several bands most likely originating from silicon.

The spectral steradiancy integrated over a 931 photomultiplier sensitivity curve was investigated as a function of time. This was carried out with the intensity unit, the output of which was displayed on an oscilloscope with a sweep speed of one microsecond per centimeter and photographed (figure 6b). The appearance of the second higher peak is easily explained. One must first note that the time constant for the decay of the discharge intensity, after all the energy has been pumped into it, is long compared to the period of the discharge current. The total energy P pumped into the system as a function of time is given by

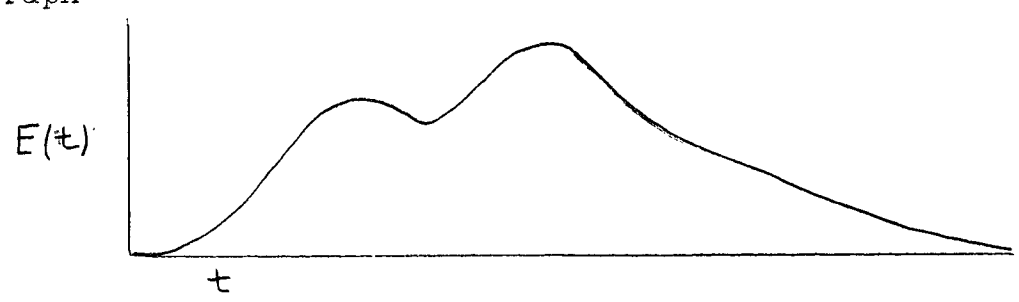
$$P(t) = \int_0^t i^2 R \, dt = R \int_0^t i^2 \, dt$$

where to a first approximation R is assumed constant during the discharge.

This integral is evaluated graphically below



Allowing for the expotential decay of the discharge energy at regions A and B in the graph above we find the energy of the discharge as a function of time is shown in the following graph



If the rate of radiation is proportional to the energy content of the discharge, as it most likely is, this will be the observed light output slightly distorted by the response curve of the photomultiplier. This distortion results from change in the distribution of energy as the temperature of the discharge is lowered.

As Spitzer[9] shows, the temperature of a plasma can be deduced from a measurement of its resistivity. The resistivity of a plasma in which electron-electron collisions are considered is given by

$$\eta = \frac{\eta_L}{\nu} \tag{22}$$

where ν is a function of the state of ionization of the gas.

Z =	1	2	3
ν =	.582	.683	.785

and η_L is the theoretical resistivity of a Lorentz gas. η_L is given by

$$\eta_L = \frac{\pi^{3/2} m_e Z e^2 c \, Ln\lambda}{2(2KT)^{3/2}} \tag{23}$$

where e is the electronic charge in esu, K the Boltzmann constant, m_e the mass of the electron, and T the absolute temperature. λ is given by

$$\lambda = \frac{3}{2} \frac{1}{Ze^3} \left(\frac{K^3 T^3}{\pi n_e} \right)^{1/2}$$

where n_e is the electron density. A table of $Ln\,\lambda$ for different values of T and n_e is given by Spitzer. Substituting the numerical values for the constants in equations 22 and 23 for a singly ionized gas we find

$$T = 3.49 \left(\frac{Ln\lambda}{n} \right)^{\frac{3}{2}} \tag{24}$$

A more convenient variable than $\mathrm{Ln}\,\lambda$ is $K = \mathrm{Ln}\,\lambda / T^{\frac{3}{2}}$. The table below gives this for different values of T and n_e.

$T^{\circ}K$	ELECTRON DENSITY electrons /cc.					
	1	10^6	10^{12}	10^{15}	10^{18}	10^{21}
10^2	1.6×10^{-2}	9.43×10^{3}				
10^3	6.21×10^{-4}	4.04×10^{-4}	1.88×10^{-4}			
10^4	2.32×10^{-5}	1.63×10^{-5}	9.43×10^{-6}	5.57×10^{-6}		
10^5	8.41×10^{-7}	6.21×10^{-7}	4.04×10^{-7}	2.97×10^{-7}	1.87×10^{-7}	
10^6	2.97×10^{-8}	2.28×10^{-8}	1.59×10^{-8}	1.24×10^{-8}	8.96×10^{-5}	5.54×10^{-9}

The temperature is best found by plotting $\log_{10}T$ against $\log_{10}K$ for the value of n_e during the discharge. n_e can be found by

$$n_e = 3.22 \times 10^{15} P \mathcal{Z}$$

where P is the final pressure of the discharge in mm. of Hg. and $\mathcal{Z}$ is the degree of ionization. K is given by

$$K = 1.53 \times 10^{-4} RA/L \qquad \text{(see equation 24)}$$

where R is resistance of the discharge; A is cross section of discharge; L is length of discharge. This equation is based on the assumption that the discharge has uniform cross section. For the present flash tube n_e has the value $n_e \approx 10^{15}$ and K has the value $K = 3.9 \times 10^{6}$. This results in an estimate of the temperature at $40 \pm 10 \times 10^{3}\ ^{\circ}K$.

It should be noted that this result depends upon a theoretical expression for η_L which is good only for low densities and high temperatures. Furthermore the theory requires

that the energy gained between collisions from the electric field be much less than the average kinetic energy. A quick check shows that the conditions of the discharge are in the domain of applicability of the theory.

This estimate was made in an attempt to establish the spectral distribution curve for the discharge. At present a more direct approach to the problem is being used. The spectral steradiancy of the discharge is compared to that of a standard carbon arc using the intensity unit attached to a monochromator.

3. Plasma Unit

The plasma unit was designed to generate a uniform plasma in a gas of any desired purity and composition. The absorption tube in which the plasma is formed is a glass tube two centimeters in diameter and fifty centimeters in length, as shown in figure 7a. Glass windows through which the flash unit light is passed are welded to each end of the absorption tube. The discharge which produces the plasma takes place between two electrodes P and N, set in side arms A and B respectively. With the electrodes in the side arms, only the plasma in the D.C. discharge of the positive column will be present in the absorption tube. The rest of the discharge will be in the side arms, and furthermore the electrodes will not obstruct the optical path. Because the electrodes are watercooled it is possible to seal them to the glass with De Khotinsky Wax, in spite of the large amount of heat generated in the order of

400 watts at the cathode for a D.C. discharge and of 10 watts for each electrode in an A.C. discharge.

Attaining a discharge of sufficient purity presented a difficult problem. During a D.C. discharge a metal film is sputtered onto the wall of side arm B. Gases will occlude on this film and when the next discharge is run the heating of the wall boils them off, releasing them to the discharge. This source of impurities is eliminated by making side arm B U-shaped and immersing it in a bath of liquid nitrogen. This procedure also freezes out a large amount of oxygen. When there is an A.C. discharge this problem occurs at both side arms A and B. However there was not sufficient time to modify side arm A. To remove the remaining active gases, a chamber to contain finely divided uranium was appended to the absorption tube. This follows the method of G. H. Dieke[10,11].

Two grams of uranium turnings, cleaned in nitric acid shortly before, are introduced into the chamber and baked for two hours at a high temperature under vacuum. Hydrogen gas is then allowed to fill the system to a pressure of about one atmosphere. The reaction of the uranium with the hydrogen was started by an initial hard heating of the turnings after which the temperature is maintained at about 250°C. In about one-half hour the effect of the reaction can be seen - whiskers form on the turnings. After several hours the reaction goes to completion leaving uranium hydride powder. The hydrogen is then pumped off and the uranium hydride is heated to 400°C to reduce

it to a finely divided uranium. This powder is prevented from entering the absorption tube by placing a wad of glass wool between the chamber and the tube. It should be noted that the uranium powder can ignite spontaneously if exposed to air.

A three litre glass resevoir guarantees a ready supply of the major constituent under study. It is located near the anode where cataphoresis may be exploited, G. H. Dieke[12]. Cataphoresis is the concentration at the cathode of the minor constituent of a mixture of gases. This works whether the minor constituent is an inert gas or a monatomic molecule. The desired gas in the resevoir will have the impurities in it swept toward the cathode and powdered uranium where they are removed, if active, and concentrated in the side arm B, if inert. If the side arm fills, the resevoir is shut off, the absorption tube pumped out, the resevoir reopened and the process started again. This is repeated until the desired purity is reached.

In summary, two main processes are used in purifying the gas, cataphoresis for the inert gases and gettering by uranium for the active gases.

Once the gas is purified the desired impurities can be introduced through the arrangement shown in figure 7b.

4. Shutter Unit

The shutter unit (figure 8) as mentioned in the introduction of this chapter, is used to control the exposure of the plasma and to time the triggering of the flash unit. There are

two diametrically opposite slots A and B in the rotating disc; Slot A, near the rim, to control the exposure by adjustment of its width, and Slot B, near the axis, to control the timing.

The minimum exposure is three milleseconds, this being determined by the $f = 20$ of the spectrograph, the speed of the disc r.p.s. = 1725, and the distance $s = 3$ cm. between the spectrograph slit and the disc. The minimum exposure is given by

$$t_{min} = \frac{ls}{f 2\pi R \times r.p.s.}$$

where $R = 3.7$ cm. is the mean distance from the axis to Slot A.

Since Slot A will expose the spectrograph about twenty-eight times per second, a compur shutter, which is open for just under the time of one revolution of the disc, is placed in front of the disc, thus limiting the number of exposures to one. This exposure will occur when the shutter is open.

The flash unit firing is timed by a pulse from the photomultiplier P_1 produced by a burst of light from the lamp L, as Slot B passes in front of the photomultiplier. This event is arranged to take place in advance of the coincidence of Slot A with the spectrograph slit by placing the photo-multiplier off the diameter formed by the spectrograph slit and the disc axis. The photomultiplier pulse is delayed by the Tektronix 545-A oscilloscope until the spectrograph slit opens. This pulse gets through to the trigger unit only if the compur shutter is open.

Low jitter in the order of ten microseconds is assured by having a large slope to the photomultiplier pulse. This slope of .2 volts per microsecond is achieved by imaging lamp B in the plain of the disc with lens L and placing stops on both sides of the image. The synchronization of the flash firing and the spectrograph opening is accomplished by the following procedure. The pulse from the photomultiplier, P_1 triggers the display sweep of the oscilloscope. Input A is connected to another photomultiplier P_2 located at the plate position of the spectrograph. A carbon arc used to simulate the plasma produces a pulse (displayed on the oscilloscope) when the spectrograph slit is open. The delayed output pulse of the oscilloscope is fed to input B and displayed. Synchronization takes place when these two pulses coincide, as the delayed pulse fires the discharge tube.

5. Electronic Units

The two remaining units of the six used in the experiment, namely the trigger unit and the intensity unit are electronic in nature.

The triggering unit was designed after the work of G.A. Theophanis[13]. Two three-meter long, type R.G. 58U coaxial cables, in parallel, are charged to 16 kv. with a high frequency and high voltage supply of the type used in television receivers. The far end of the cables is terminated with a 50 $\mu\mu$ farads 20 kv. condenser in series with ten one-megohm resistors, in parallel, arranged about the condenser. This is essentially an infinite termination. The sheaths of the coaxial

cables are grounded while the inner conductors at 16 kv. are connected to the anode of a hydrogen filled thyatron. When a signal is applied to the grid of the thyatron it shorts the end of the attached cable. Since the cables are at 16 kv. this sends a - 16 kv. pulse down the cable which is reflected with a coefficient of +1. In order that the voltage across the condensor remains constant, e.g. 16 kv., the far side must fall to -32 kv. This pulse is then taken off across the resistors.

The hydrogen thyatron is fired with a 2D21 which is fired in turn from a delay pulse. The compur shutter is connected to the grid circuit of the 2D21 so that control is exercised over the firing of this tube. The turn on time of the 2D21 is longer than the duration of the delayed pulse from the oscilloscope, so a univibrator was introduced into the circuit with an output pulse of 50 microseconds duration. This introduced a delay of 35 microseconds with a jitter time of five microseconds. With this jitter, the total jitter time of the system mounts to about 25 microseconds.

The intensity unit is used to determine the integrated light output for the flash unit, and will be used to determine the spectral distribution of the output as compared with that of a carbon arc. This unit consisting of a photomultiplier 931A and a transistor (type 2N1177, 144 mc. alpha cut off frequency) is completely enclosed, with its power supplies, in a brass box. It is necessary to use this particular design in

order to avoid pickup of the electrical noise from the discharge. The transistor is in the common collector configuration, so matching the high generator impedence of the photomultiplier 931A with the 52 ohm characteristic impedence of the cables connecting it to the oscilloscope is made possible. By arranging an impedence match at the oscilloscope end also, there is very low noise pickup from the cable. This unit works very satisfactorily.

Besides the units designed and constructed for the experiment, several other pieces of available equipment are used. They are: a Tektronix oscilloscope type 545A, a tuned grid 28 megacycle oscillator, a Jarrell-Ash microphotometer, Hilger automatic glass-quartz spectrograph and two high voltage supplies, one for the plasma unit capable of delivering two amperes at 1200 volts, the other for the flash unit capable of 30,000 volts at 30 milliamperes.

Chapter III

RESULTS AND CONCLUSIONS

1. Introduction

Upon completion of the construction of the present apparatus, a preliminary experiment was run to demonstrate the effectiveness of the theory and apparatus. There follows in this chapter an account of the experiment with its results and conclusions suggesting efficient operating conditions and possible improvements in the equipment. In addition, experiments in which the flash unit could effectively be used are proposed.

2. Experiment

Neon was chosen as the gas in which the discharge occurs, since in future experiments its use will enable the results to be compared with the investigations of Kopfermann and Ladenberg. The discharge, taking place in the neon at a pressure of 2.2 millimeters, was excited by the radio frequency oscillator generating about 20 watts, an unknown fraction being dissipated in the discharge. This energy was introduced through the two electrodes P and N. The neon was not free of impurities in spite of the aids employed since the metal components of the absorption tube outgassed too rapidly. It should be noted that the apparatus was carefully arranged so that all portions of it would flood the spectroscope prism.

The data obtained is derived from one plate containing four spectrograms. One consisted of an emission spectrum only. Two consisted of six shots each of the spectrum resulting from

the passage of the continuum light through the neon plasma. These twelve shots were taken through the same discharge tube window. These two spectrograms differed by having an exposure time t_e, equal to .45 milliseconds for one and .76 milliseconds for the other. The fourth spectrogram consisted of a twenty-five shot exposure of the continuum source only through a seven step graded filter (platinum on glass, essentially a neutral filter for the wave length range studied). Uniform illumination of the plate was assured by forming an image of the discharge on the collimator lens of the spectrograph with a lens in close proximity to the step filter and spectrograph slit. The flash continuum, rather than other sources, was used to establish the characteristic curve by exposure of the plate through the step wedge since this exposure must be made under the same conditions as were the spectrograms to which the curve would be applied.

The pertinent data and results for the different lines examined are given in the table below.

Line	6163	6143	6334	6074	6096
Trans- From	$3p(^3P_1)$	$3p(^1P_1)$	$3p(^3D_2)$	$3p(^3P_o)$	$3p(^3P_2)$
ition To	$3s(^3P_o)$	$3s(^3P_2)$	$3s(^3P_2)$	$3s(^3P_1)$	$3s(^3P_1)$
te_1	$.45\times10^{-3}$ sec.				
te_2	$.76\times10^{-3}$ sec.				
t_d	$.45\times10^{-6}$ sec.	54×10^{-6} sec.	$.65\times10^{-6}$	$.57\times10^{-6}$	$.58\times10^{-6}$ sec.
$B(T)/B(T^1)$	.0044	.0036	.0030	.0034	.0034
r_p		1.02		1	
T	4730	4240	4000	4220	4200

For the two pairs of transitions with different common lower levels $^3P_1$ and $^3P_2$, the ratio r_p of the values $B(T)/B(T^1)$ gives the relative population of the upper states of each pair. The temperature T is calculated on the assumption that the discharge is a 40,000 ^oK black body. The transition temperatures appear to be quite reasonable, since when a carbon arc at a temperature of about 5000 ^oK was used as a continuum source, the lines were seen faintly in absorption.

During the construction of the apparatus many plates were taken upon which no calibration exposures were made but which did show interesting results. One plate revealed sixteen transitions in absorption between the 3p5.3p and 3p5.3s configurations, while another plate showed two transitions which, to the best of our knowledge, have never been reported as seen in absorption. These transitions occurred between the states $^3P_1(2p^5 3p) - {}^3P_2(2p^5 5s)$ and $^3P_o(2p^5 3p) - {}^3P_1(2p^5 5s)$.

The values of $B(T)/B(T^1)$ are in error by at most 30% estimated by tracing the maximum errors in measurements through the calculations involved. There are three important sources of random error; arising from measurements of time, density and intensity. The greatest difficulty in the measurement of the time t_e, resulting in an error of 5%, is caused by the finite mechanical opening time of the slit. In the determination of the percentage transmission of the plate an error of about 2% arises, not from the Jarrell-Ash microdensitometer which is used for the measurement, but rather from the general noise level of the plate.

The absorption line appears as only a 4% variation of the continuum, and since the difference between the absorption and background exposures is used in these calculations, a large source of error is introduced. This error could be diminished considerably by shortening the exposure time t_{el}. The third error arises from the graphical evaluation of the exposure from the transmission of the photographic plate. The twenty-five shots used to establish the characteristic curve resulted in over-exposure, allowing only the lower portion of the curve to be well established. However, only an approximate curve is needed, since small variations in exposure are measured. Unfortunately, this inaccurate curve did not allow the second method, mentioned in Chapter I and requiring a measurement of both emission and absorption spectra, to be used since large variations in exposure are involved.

Besides the above random errors, several systematic ones were present. All the formulas developed in Chapter I were dependent upon an integral over line width, but since the lines are so slightly in absorption or emission, the maximum depth or height of the lines was taken as a measure of their integrals, that is, it was assumed that they all have the same line shape. Another error is introduced by the progressive darkening of the window from the discharge debris. This was allowed for in a first approximation by assuming that the two sets of exposures were taken with black bodies of different temperatures, necessitating the use of the slightly modified formula

$$td = \frac{(P_1^b - P_1)(te_2 + t_a) - (P_2^b - P_2)(t_{e1} + t_a)}{(P_2 - rP_1)} - ta$$

instead of equation 17a where $r = P_2^b/P_1^b$ and P_1^b and P_2^b are background intensities of the exposures 1 and 2. The other symbols are the same as those in Chapter I. If it is assumed that a fixed quantity of material is deposited on the window after each discharge, then the exposure of the plate from the n^{th} discharge is given by

$$P_m = cT^{m-1}$$

where T is the transmission.

By measuring the above plate we find T = .9938. It has been explicitly assumed in calculating the temperature of the plasma that the plasma column examined was uniform and at a common temperature. The diameter of the absorption tube, 2 cms., may make this assumption invalid. Another error which is as yet undetermined results from the time behavior of the temperature of the flash discharge. Since the source peaks at a very high temperature this error would be relatively small.

Other errors which may be important result from an intermittancy effect and the failure of the Reciprocity Law. The intermittancy effect will arise from the superposition of the six shots, with a time interval of about one minute, to form a single spectrogram. The Reciprocity Law may fail because of the different exposure times of the continuum and plasma; and of the step wedge and spectrograms. It is believed however

that this error will be slight because of the short times and high intensities involved.

3. Future Work

After running the experiment, areas which are open to improvement became evident. To observe transitions at higher temperatures it will be necessary to construct a shuttering mechanism with an open time approaching that of the duration of the flash. This short time will partially eliminate the difficulties caused by the intermittancy effect since the exposures of the plasmas which at present are for time t_e, will be composed of a series of exposures each of duration t_a but which will total to time t_e. To avoid difficulties encountered with the purity of the neon, it is suggested that an absorption tube be built which will be entirely free of electrodes but still incorporates uranium as a getter. In this tube the plasma would be generated by an electrodeless R.F. discharge.

From a detailed study of the time behavior of the discharge spectrum a better estimate of time t_a would be available. It is also recommended that the spectral radiancy of the source be compared to that of a standard black body so that transition temperatures may be determined with a degree of certainty. Further investigations of the discharge may suggest changes in the design of the flash unit to improve on the uniformity of the continuum.

It is hoped that in the future several interesting and important experiments will be conducted with this flash unit.

The adaptation of this technique to the study of transient plasmas is of considerable interest to work in this laboratory, since it may be used to check assumptions made in determining temperatures of shock generated plasmas. Another projected experiment will determine the effect of impurities on the relative population densities of a steady state plasma, a work of current interest in the development of optical masers . Absorption studies of plasmas are very likely to become a very important diagnostic technique now that high temperature continuum sources are available.

Appendix I

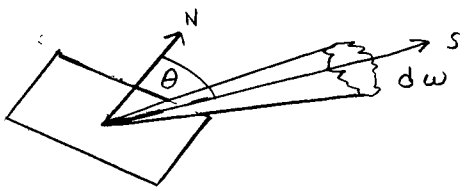
THE EQUATION OF TRANSFER

1. Definitions and Fundamental Notions.

(a) The specific intensity of radiation at a point P and in a given direction: Consider a point in a field of radiation. Through this point construct a small elemental surface $d\sigma$; in a specific direction s construct cones of solid angle $d\omega$, with apex on ds at every point of $d\sigma$. Then during the time interval dt, the energy traversing the area $d\sigma$ and from the semi-infinite volume so defined can be written as

$$dE = I \cos\theta \quad d\omega \, d\sigma \, dt. \qquad (A1)$$

where θ is the angle between s and the normal to $d\sigma$.



I obviously depends upon the point P and the direction s. It is called the specific intensity or steradiancy at the point P and in the direction s. In an isotropic radiation field I is independent of s.

(b) Monochromatic Specific Intensity. The monochromatic specific intensity is so defined that

$$I_\nu \cos\theta \, d\sigma \quad d\omega \quad dt \quad d\nu \qquad (A2)$$

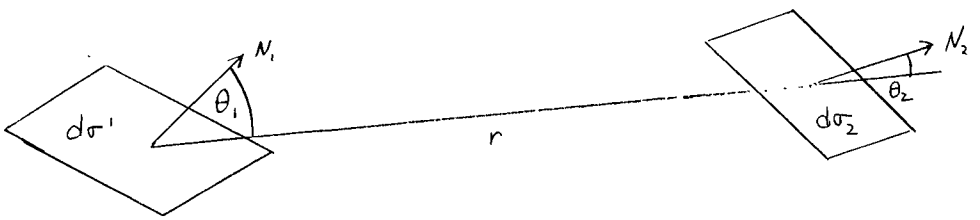
is the total energy in the frequency interval (ν , $\nu + d\nu$) which crossed the elemental area $d\sigma$ in the direction θ , in a solid angle $d\omega$ and in time dt. From the definition

it follows that

$$\int_0^\infty I_\nu \, d\nu = I .$$

We call I the integrated intensity.

(c) Amount of Radiant Energy Flowing Through One Element of Surface to Another.



Let I be the specific intensity at P_1, in the direction of P_1P_2. The energy which traverses $d\sigma_1$ in unit time and which also traversed $d\sigma_2$ is from Equation (A1)

$$dE = I \cos \theta_1 \, d\sigma \, d\omega \, dt$$

where $d\omega$ is the solid angle that $d\sigma_2$ makes at P_1. That is,

$$d\omega_1 = \frac{\cos \theta_2 \, d\sigma_2}{r^2}$$

so

$$dE = I \cos \theta_1 \frac{\cos \theta_2 \, d\sigma_1 \, d\sigma_2 \, dt}{r^2} . \quad (A3)$$

(d) Energy Density of Radiation at a Point. The energy density, u, of the integrated radiation at a given point, is the amount of radiant energy per unit volume which is in course of transit, per unit time, in the neighborhood of the point considered. Consider a point P surrounded by a small volume V of convex bounding surface σ. Surround the volume with

another convex surface Σ such that the linear dimensions of Σ are large compared to those of σ , but small enough that the intensity in a given direction is constant for all points inside Σ. All radiation crossing V must have crossed Σ. Consider $d\Sigma$ an element through which some of the radiation has passed. The energy flowing across $d\Sigma$ and $d\sigma$, an element of σ , is from Equation (A3)

$$dE = \frac{I \cos\theta \cos\theta \, d\sigma \, d\Sigma}{r^2} .$$

Let l be the distance traversed by this radiation through V. The time of travel is l/c where c is the velocity of light. Hence the amount of radiant energy due to this pencil of light is

$$I \frac{\cos\theta \cos\theta \, d\sigma \, d\Sigma}{r^2} \frac{l}{c} .$$

But the element of volume dV of V intercepted by this ray is

$$dV = d\sigma \cos\theta \, l.$$

The solid angle subtended by $d\Sigma$ at P is

$$d\omega = \frac{\cos\theta \, d\Sigma}{r^2} .$$

Hence the total energy E in transit through the volume V is

$$E = \frac{1}{c} \int\int I \, dV \, d\omega = \frac{V}{c} \int I \, d\omega ,$$

The energy density $u \equiv \frac{E}{V} = \frac{1}{c} \int I \, d\omega .$ (A4)

If the radiation is isotropic $u = \frac{4\pi}{c} I.$

This follows identically for I_ν and u_ν also.

(e) The Emission Coefficient: Consider an element of mass m. The amount of energy emitted by this element into a solid angle $d\omega$ in time dt in a frequency interval $(\nu, \nu+d\nu)$ is given by

$$j_\nu \quad m \quad d\omega \quad dt \quad d\nu, \tag{A5}$$

j_ν is called the emission coefficient. To get a physical interpretation of this we discuss the details of the atomic processes involved.

If there are transitions of atoms of the medium from quantum state u to L then the frequency of radiation is given by

$$h\,\nu_{uL} = E_u - E_L \tag{A6}$$

where E_u and E_L are the energies of the two corresponding states. This emission process is described by the Einstein coefficients A_{uL} and B_{uL}. They are defined as follows. The probability that in an interval of time dt an atom in the excited state u emits a quantum of energy $h\,\nu_{uL}$ in the direction confined to an element of solid angle $d\omega$, and in the absence of an external radiation field is

$$A_{uL} \quad d\omega \quad dt. \tag{A7}$$

This spontaneous emission is uniform in all directions. If the atom is exposed to a radiation field the probability of a transition increases. This is taken care of by introducing B_{uL} defined in such a way that the probability that an excited atom in state u is stimulated by an external radiation field to emit a quantum $h\,\nu_{uL}$ in the direction specified by $d\omega$, in time dt is

$$B_{uL} \quad I_{\nu_{uL}} \quad d\omega \quad dt. \tag{A8}$$

where $I_{\nu_{uL}}$ is in the direction defined by $d\omega$. That is, the emission takes place in exactly the same direction as the incident radiation. The total energy emitted by a single atom per unit time, by Equations (A7) and (A8) is

$$h\nu_{uL} \quad (A_{uL} + B_{uL} I_{\nu uL})\, d\omega = h\nu_{uL} \left(4\pi A_{uL} + B_{uL} \int I_{\nu uL}\, d\omega\right).$$

If there are $N_u \nu_{uL}$ atoms per unit volume in the state u which can radiate at frequency ν_{uL}, from Equation (A5) we see that

$$j_{\nu uL} = \quad (A_{uL} + B_{uL} I_{\nu uL})\, h\nu_{uL}\, \frac{N_u \nu_{uL}}{d} \qquad (A9)$$

where d is the density.

Einstein's coefficients are also defined for emission and absorption in isotropic energy densities and intensities. The relationship between these coefficients is shown below. The total number of transitions per unit time per atom must be the same under any system. Hence

$$a_{uL} + b_{uL} U_{\nu uL} = 4\pi A_{uL} + B_{uL} \int I_{\nu uL}\, d\omega$$

where a_{uL} and b_{uL} are defined for isotropic energy densities but

$$u_{uL} = \frac{1}{c} \int I_{\nu uL}\, d\omega$$

so

$$a_{uL} = 4\pi A_{uL} \qquad \text{and} \qquad b_{uL} = C B_{uL}$$

Also

$$a^1_{uL} + b^1_{uL} I_{\nu uL} = 4 A_{uL} + B_{uL} \int I_{\nu uL}\, d\omega$$

where a^1_{uL} and b^1_{uL} are defined for isotropic intensities.

For isotropic intensities

$$\int I_{\nu uL}\, d\omega = I_{\nu uL}\, 4\pi .$$

Hence

$$a^1_{uL} = 4\pi A_{uL} \qquad \text{and} \qquad b^1_{uL} = 4\pi B_{uL} .$$

(f) The Absorption Coefficient. A pencil of radiation traversing a medium will be weakened by absorption. If the specific intensity I_ν of radiation at frequency becomes $I_\nu + dI_\nu$ after it has traversed a medium of thickness ds, we can write

$$dI_\nu = -k\, I_\nu\, ds \qquad \text{(A10)}$$

It should be remarked that $I_\nu + dI_\nu$ is the intensity of the emergent radiation which is in phase with the incident radiation. The quantity k_ν so introduced is defined as the "mass absorption coefficient" for radiation of frequency ν.

If we consider the case of absorption between two stationary states u and L, then the absorption of radiation of frequency ν_{uL} arises from the excitation of the atoms from the lower state L to the higher state u. We express this quantitatively in terms of the Einstein coefficient of absorption B_{Lu}, defined in such a way that the probability of an atom in the state L, exposed to radiation of frequency ν_{uL}, absorbing a quantum $h\nu_{uL}$ in time dt is given by

$$B_{Lu} \int I_{\nu uL}\, d\omega\, dt \qquad \text{(A11)}$$

where the integral is extended over the complete sphere.

(g) Total Absorption. Consider an element of mass m exposed to a radiation field. To calculate the amount of radiation energy absorbed in frequency interval $d\nu$ per unit time, enclose the mass in a large surface Σ chosen such that the bounding surface σ of m has linear dimensions smaller than Σ. The energy passing an element $d\Sigma$ of Σ and incident upon $d\sigma$, an element of σ, is from Equation (A3)

$$dE = I_\nu \frac{\cos\theta \cos\theta}{r^2} d\sigma \; d\Sigma \; d\nu$$

of this energy the amount absorbed from the pencil when traversing length l of the mass: $k_\nu \; l \; dE$ that is

$$I_\nu \frac{\cos\theta \cos\theta}{r^2} d\sigma \; d\Sigma \; d\nu \; k_\nu \; l$$

$$= I_\nu \; k \; dm \; d\nu \; d\omega$$

where $dm = l \cos\theta \, d\sigma \, d\delta$ is an element of mass of m and $d\omega = \frac{d\Sigma \cos\theta}{r^2}$ the solid angle subtended at the mass point by $d\Sigma$. The total energy absorbed is

$$d\nu \iint I_\nu \; k_\nu \; dm \; d\omega = d\nu \; k_\nu \; m \int I_\nu \; d\omega.$$

If the number of atoms in state L present per unit volume which can absorb energy at this frequency, ν_{uL} are $N_{L\nu_{uL}}$ the total amount absorbed by them by Equation (A11) is

$$d\nu \; h\nu_{uL} \frac{m}{d} d\nu \, N_{L\nu_{uL}} \; B_{Lu} \int I_{\nu_{uL}} \, d\omega$$

hence $$k_{\nu_{uL}} = \frac{h\nu_{uL} \, N_{L\nu_{uL}} \, B_{Lu}}{d}. \qquad (A12)$$

2. The equation of transfer.

Consider a small cylinder of crossection $d\sigma$ and length ds normal to $d\sigma$, Let I_ν be the intensity of the radiation of frequency incident on one face of the cylinder in the s direction. The intensity emergent from the second face in the same direction is $I_\nu + dI_\nu$. The amount of radiant energy crossing in time dt and in the direction of the solid angle $d\omega$ about s is

$$I_\nu \; d\nu \; d\omega \; d\sigma \; dt,$$

of this

$$k_\nu \; d \quad ds \quad I_\nu \; d\nu \; d\omega \; d\sigma \; dt$$

is absorbed by the cylinder; the amount radiated is

$$d \quad ds \quad d\sigma \quad j_\nu \quad d\omega \; d\sigma \; dt$$

hence in the steady state

$$d \; I_\nu \; d\nu \; d\omega \; d\sigma \; dt = d(\; j_\nu - k_\nu \; I_\nu \;) \; \sigma \; d\nu \; d\omega \; dt \; ds$$

$$\text{i.e.} \quad \frac{d \; I_\nu}{ds} = d(j_\nu - k_\nu \; I_\nu). \qquad \text{(A13)}$$

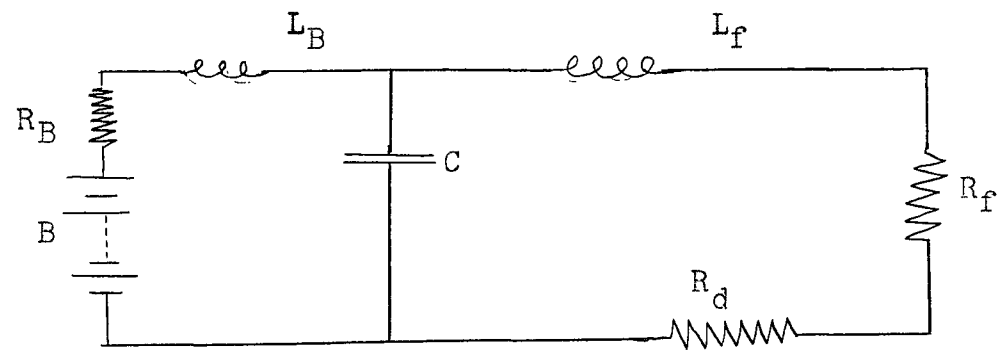
This is the equation of Transfer. We can write this equation in terms of Einstein's coefficients using equations (A9) and (A12).

$$d \; I_{\nu \; uL} = N_u \nu_{uL} \; (A_{uL} + B_{uL} \; I_{\nu uL}) h\nu_{uL} - N_L \; {}_{uL} \; B_{Lu} h\nu_{uL} I_{\nu uL} \qquad \text{(A14)}$$

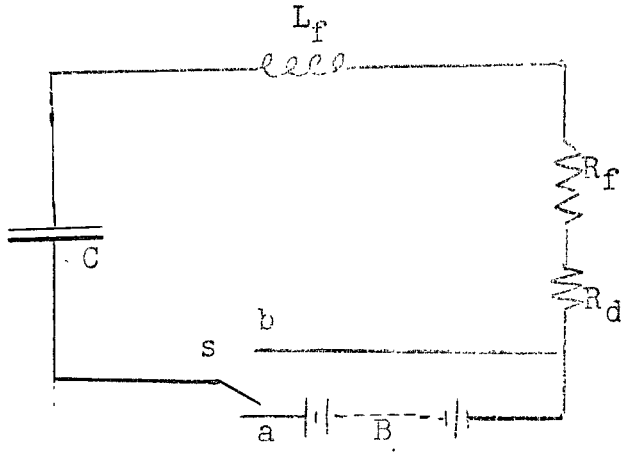
Appendix II

DISCHARGE MODEL

A model for the electric circuit of the flash unit is shown below.



It is derived from an obvious correspondence between physical elements of the unit and common circuit elements. C is a capacitor of 1.6 microfarads or that of the flash unit capacitor. The inductance L_f represents the inductance of the unit condenser and leads, about 37 milli microhenries. The resistances R_f and R_d assume the values of the lead and discharge resistances respectively. The Battery B represents the charging unit with R_B the charging resistance 200 K ohms and L_B the charging inductance. When the discharge is triggered the charging unit resistor R_B and inductance L_B essentially disconnect the battery B from the condenser as $R_BC \approx 3.2$ seconds while the discharge period is about three microseconds. Thus we simplify the circuit to that shown below



The equation for this circuit is

$$R_t \frac{d^2i}{dt^2} + R_t \frac{di}{dt} + \frac{i}{c} = 0$$

where $R_t = R_f + R_d$. The appropriate solution when the switch s is moved from contact a to contact b at time t = 0 is

$$i = \frac{B}{\eta L} e^{-\frac{RT}{2L}} \sin \eta t \qquad \text{(A15)}$$

where

$$\eta = \left\{ \frac{1}{Lc} - \left(\frac{R}{2L}\right)^2 \right\}^{\frac{1}{2}}. \qquad \text{(A16)}$$

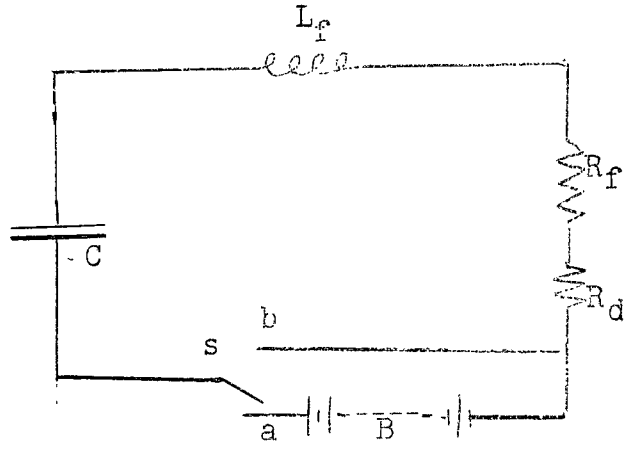
The switching corresponds to triggering the discharge. From equation (A1) the time derivative of the current is

$$\frac{di}{dt} = \frac{B}{\eta L} e^{\frac{-Rt}{2L}} \left(\eta \cos \eta t - \frac{R}{2L} \sin \eta t \right)$$

or

$$= \frac{B}{\eta L^{3/2} c^{\frac{1}{2}}} e^{\frac{-Rt}{2L}} \cos (\eta t + \theta) \qquad \text{(A17)}$$

where $\theta = \arctan \frac{R}{2L\eta}$.



The equation for this circuit is

$$R_t \frac{d^2i}{dt^2} + R_t \frac{di}{dt} + \frac{i}{c} = 0$$

where $R_t = R_f + R_d$. The appropriate solution when the switch s is moved from contact a to contact b at time t = 0 is

$$i = \frac{B}{\eta L} e^{-\frac{RT}{2L}} \sin \eta t \qquad \text{(A15)}$$

where

$$\eta = \left\{ \frac{1}{Lc} - \left(\frac{R}{2L}\right)^2 \right\}^{\frac{1}{2}}. \qquad \text{(A16)}$$

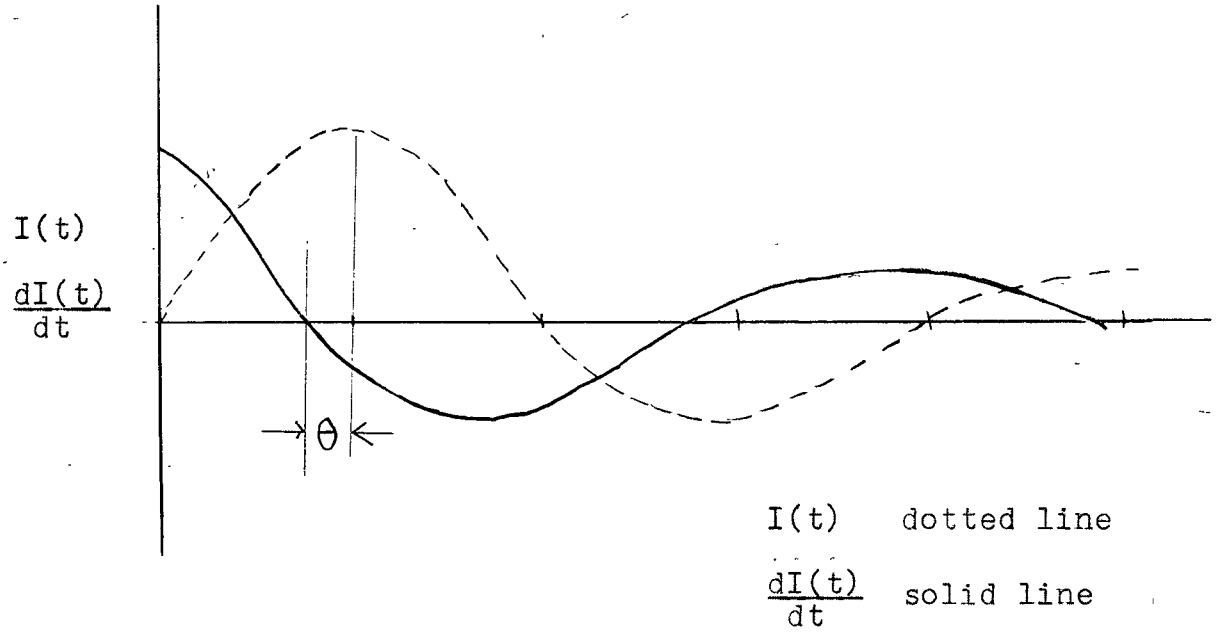
The switching corresponds to triggering the discharge. From equation (A1) the time derivative of the current is

$$\frac{di}{dt} = \frac{B}{\eta L} e^{\frac{-Rt}{2L}} \left(\eta \cos \eta t - \frac{R}{2L} \sin \eta t \right)$$

or

$$= \frac{B}{\eta L^{3/2} c^{\frac{1}{2}}} e^{\frac{-Rt}{2L}} \cos (\eta t + \theta) \qquad \text{(A17)}$$

where $\theta = \arctan \frac{R}{2L\eta}$.



The logarithamic decriment LD defined by

$$(LD) = \log_e \left(\frac{di}{dt} \right)_T \Big/ \left(\frac{di}{dt} \right)_{T + 2\pi}$$

is given by

$$(LD) = \frac{2\pi}{\eta} \frac{R_t}{2L_f} . \qquad (A18)$$

With the expression A3 and A4 it is possible to calculate b: . R_t and L_f for a discharge by observing $\frac{di}{dt}$. Measuring LD and P the period we have $L = \frac{P^2}{c} \frac{1}{4\pi^2 + (LD)^2}$ and $R = \frac{L}{P}(LD)$.

BIBLIOGRAPHY

1. Garton, W.R.S., Proceedings of the 4th International Conference of Ionization Phenomena in Gases, 1960, IID 518.

2. Garton, W.R.S., and Rajaratnama, A., 1957, Proceedings of the Royal Society, A70 815.

3. Ladenberg, R., 1934, Reviews of Modern Physics, 5 243.

4. Korff, S.A., and Breit, G., 1932, Reviews of Modern Physics, 4 471.

5. Ladenberg, R., and Levy, S., 1930, Zeitschrift Fur Physik, 65 189.

6. Francis, G., Ionization Phenomena in Gases, Page 90.

7. Anderson, J.A., 1932, Astrophysics, J 75 394.

8. Kofoid, J.M., 1960, Power Apparatus and Systems, 51 999.

9. Spitzer, L., Physics of Fully Ionized Gases, P. 81.

10. Dieke, G.H., and Crosswhite, H.M., 1954, Journal of Applied Physics, 25, 196.

11. Dieke, G.H., and Cunningham, S.P., 1952, Journal of the Optical Society of America, 42 187.

12. Riesz, R., and Dieke, G.H., 1954, Journal of Applied Physics, 25, 196.

13. Theophanis, G.A., 1960, Review of Scientific Instruments, 31, 4.

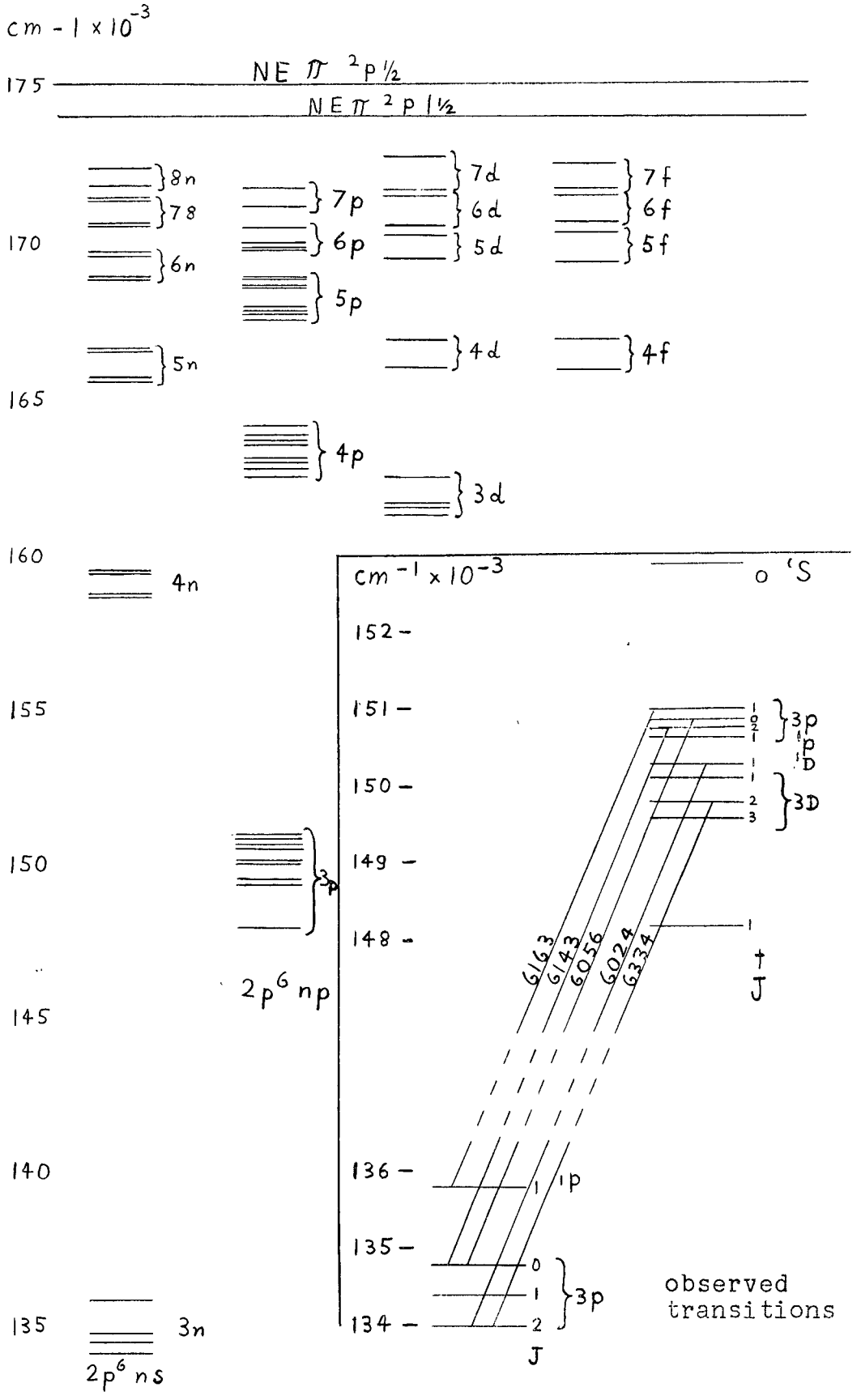


FIGURE 1 - NEON LEVELS

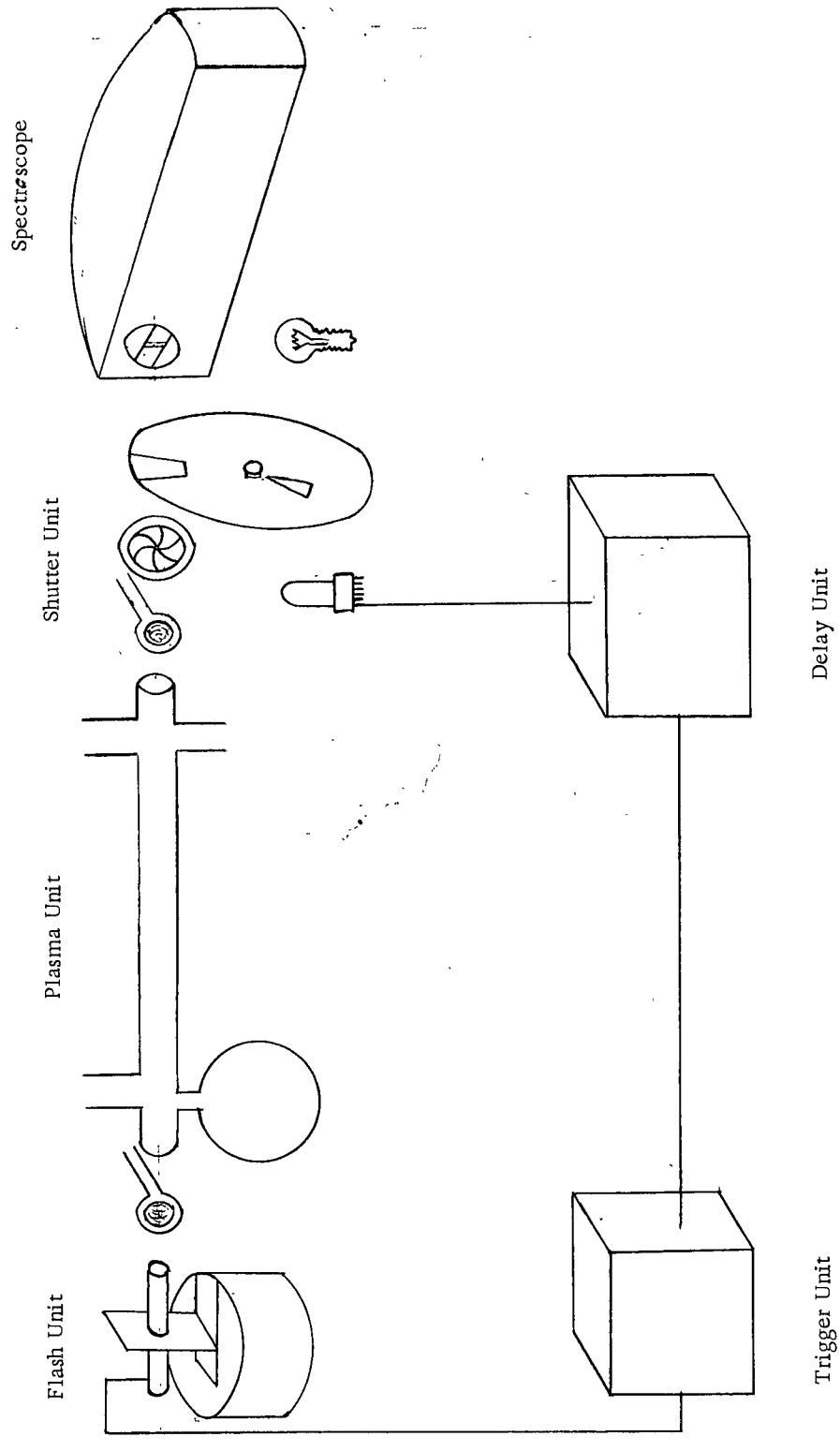


FIGURE 2 - APPARATUS

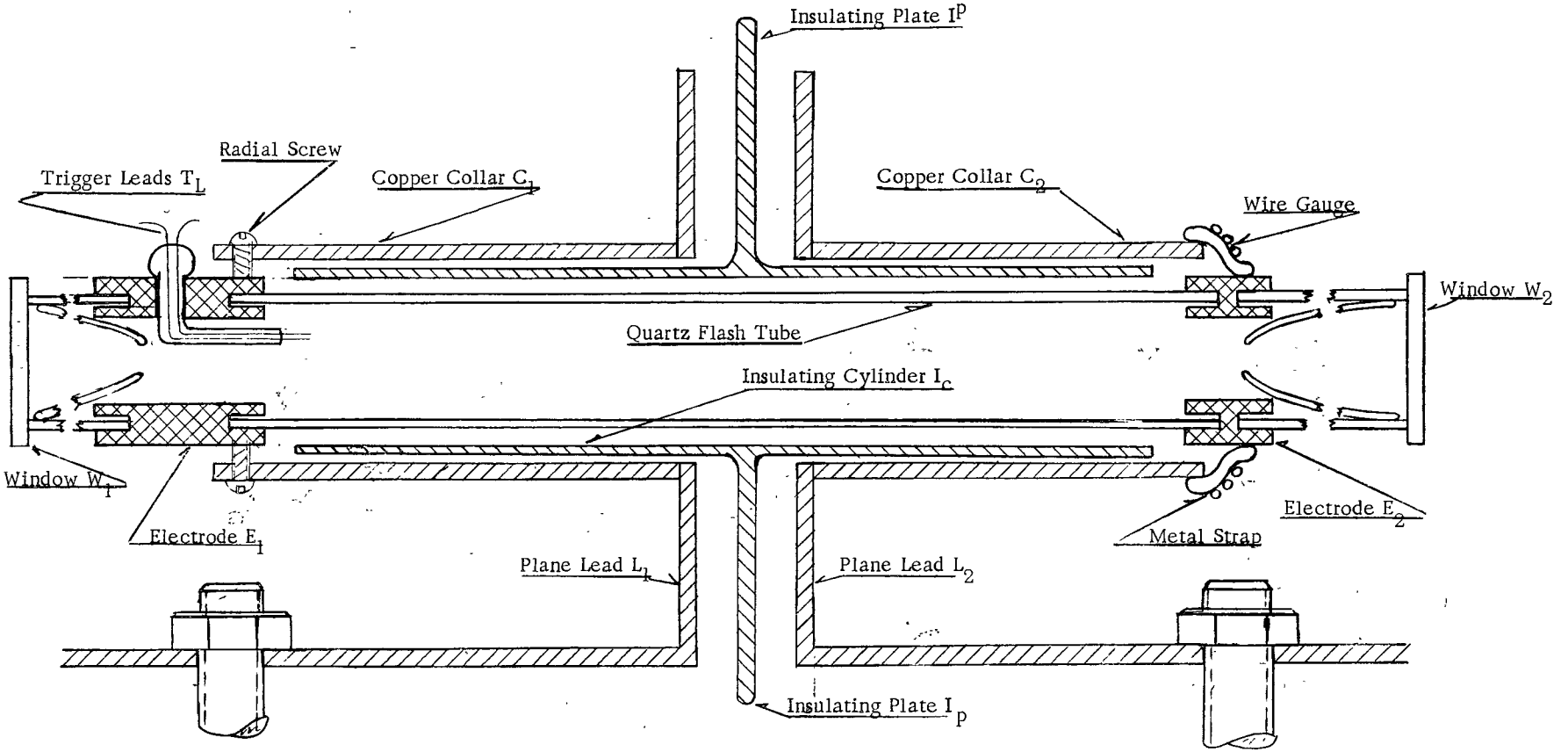


FIGURE 3 - THE FLASH UNIT

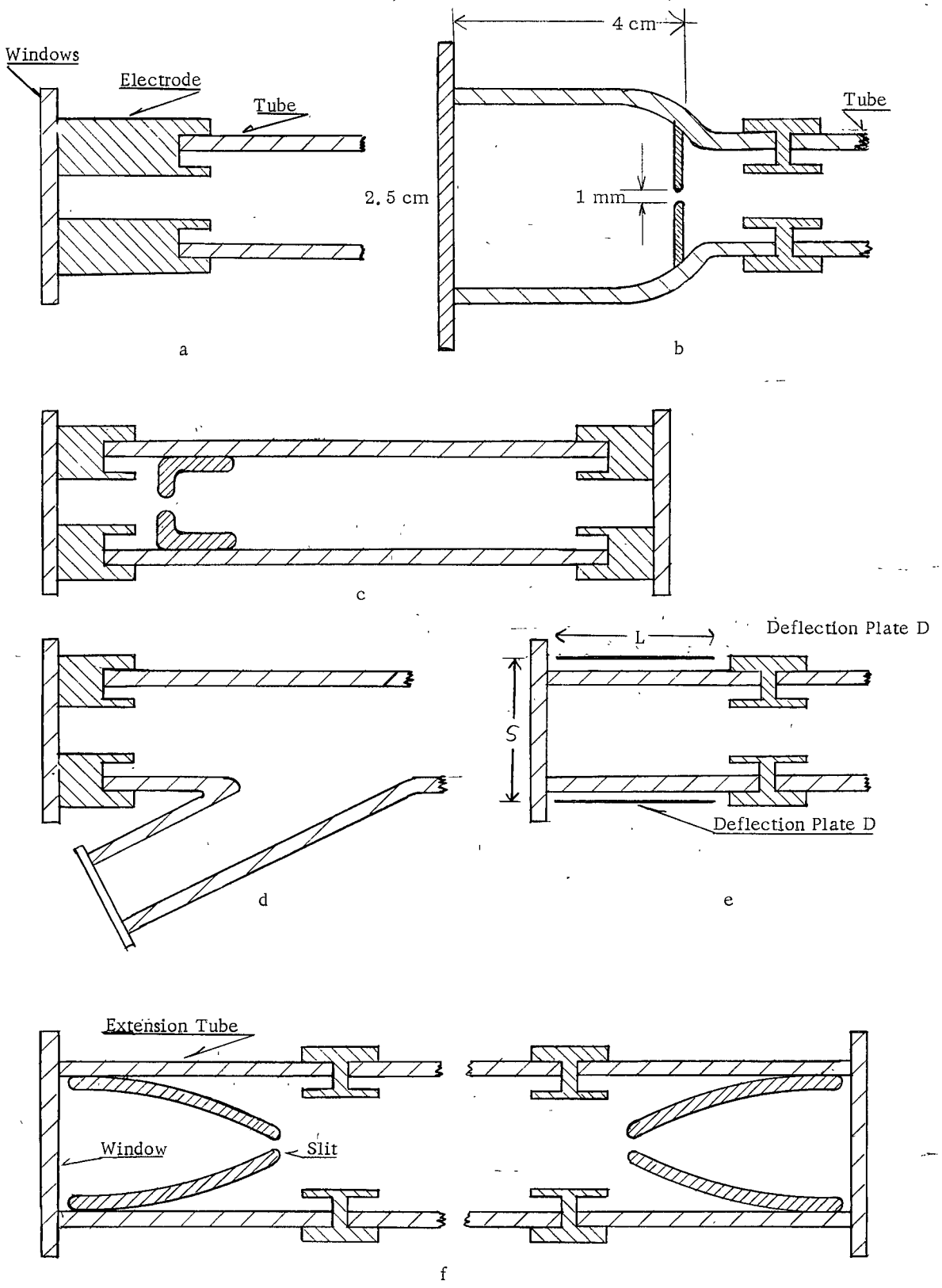
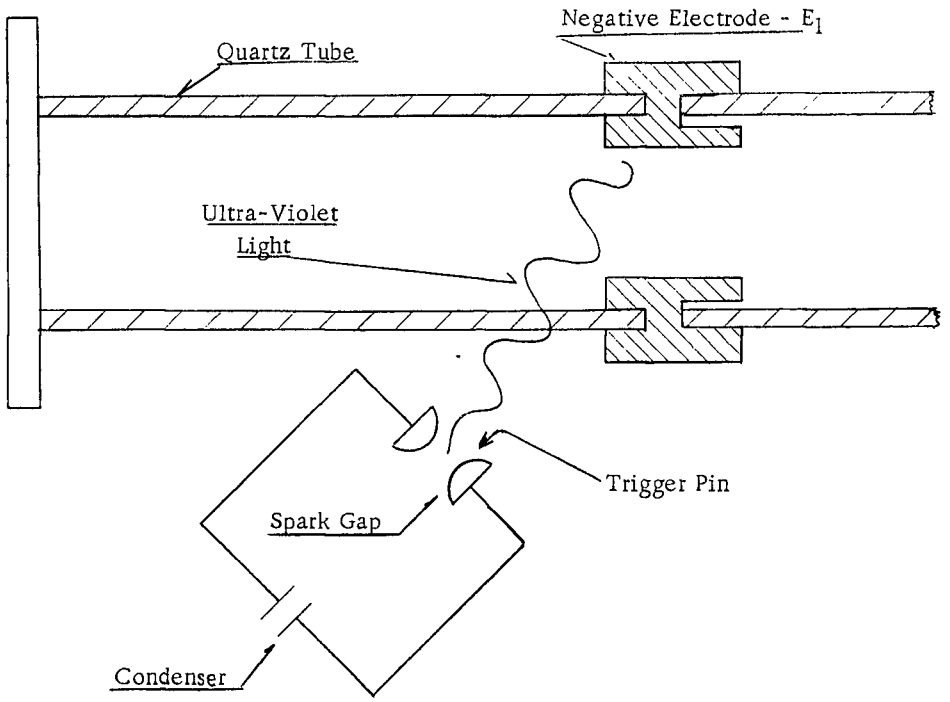
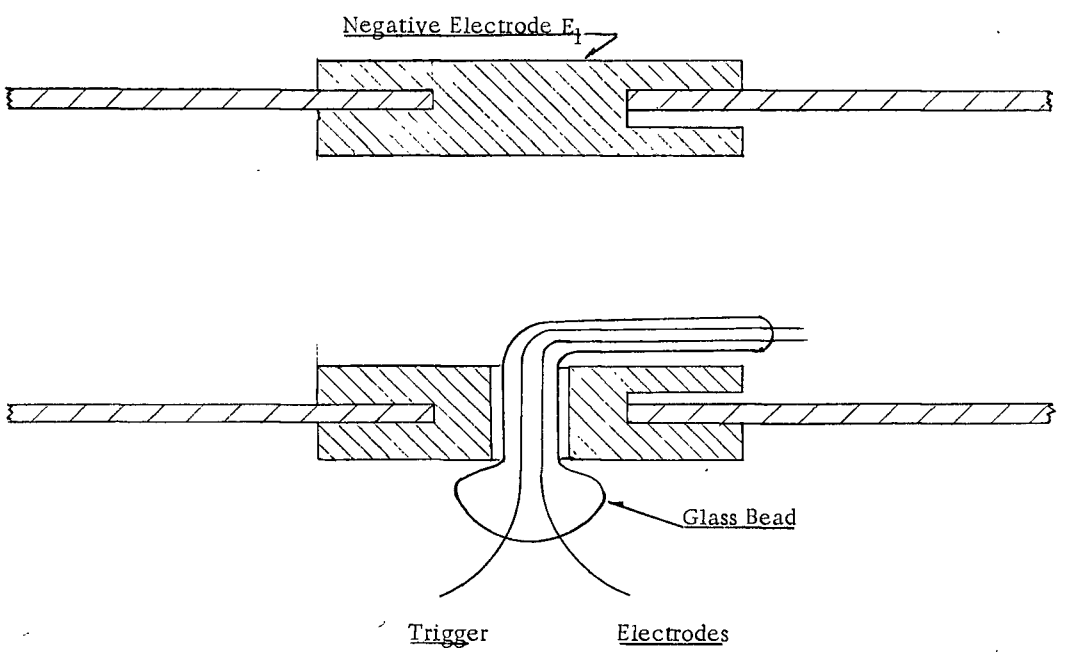


FIGURE 4 - WINDOW GEOMETRIES



a



b

FIGURE 5 - TRIGGERING GEOMETRIES

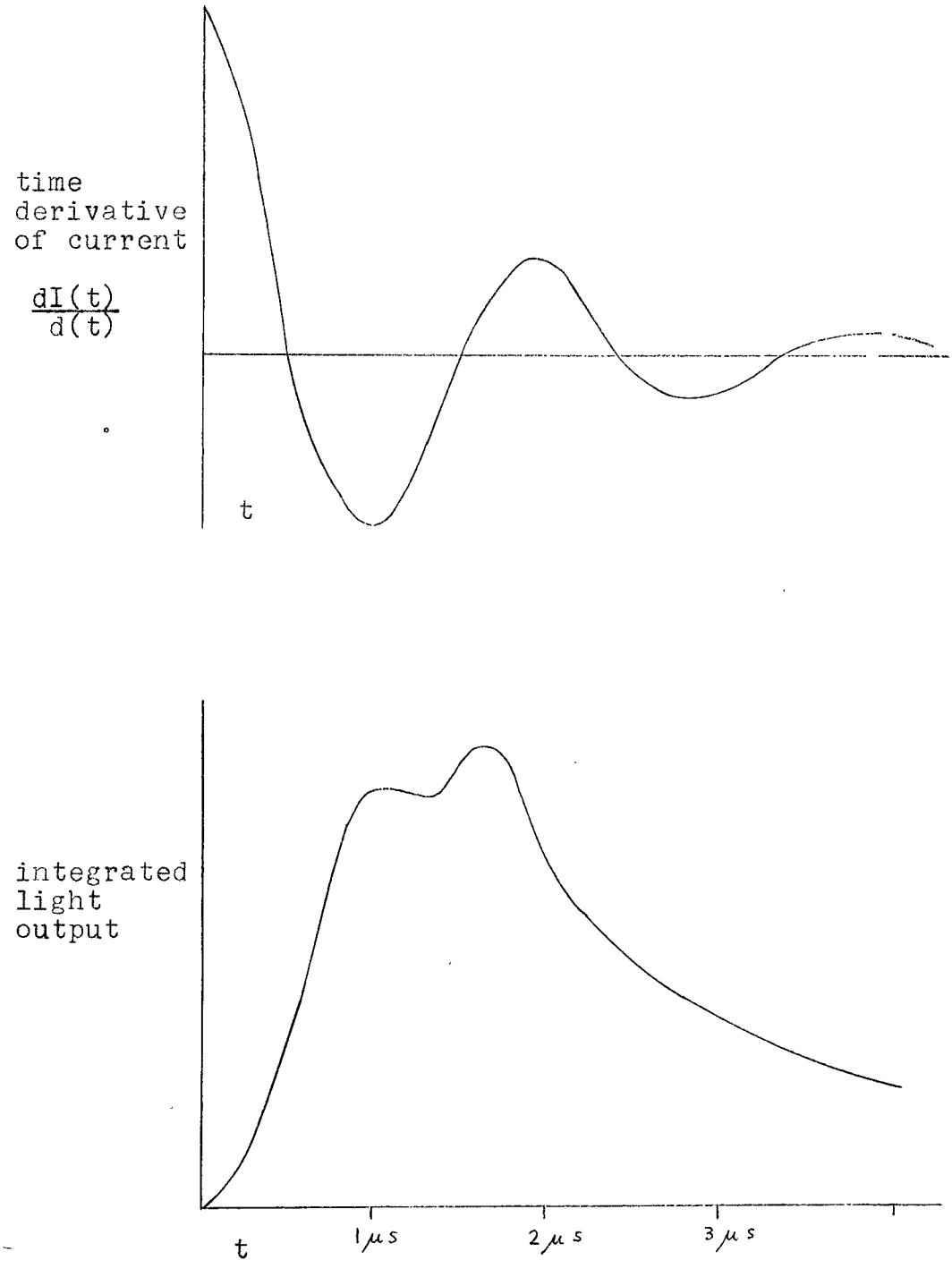
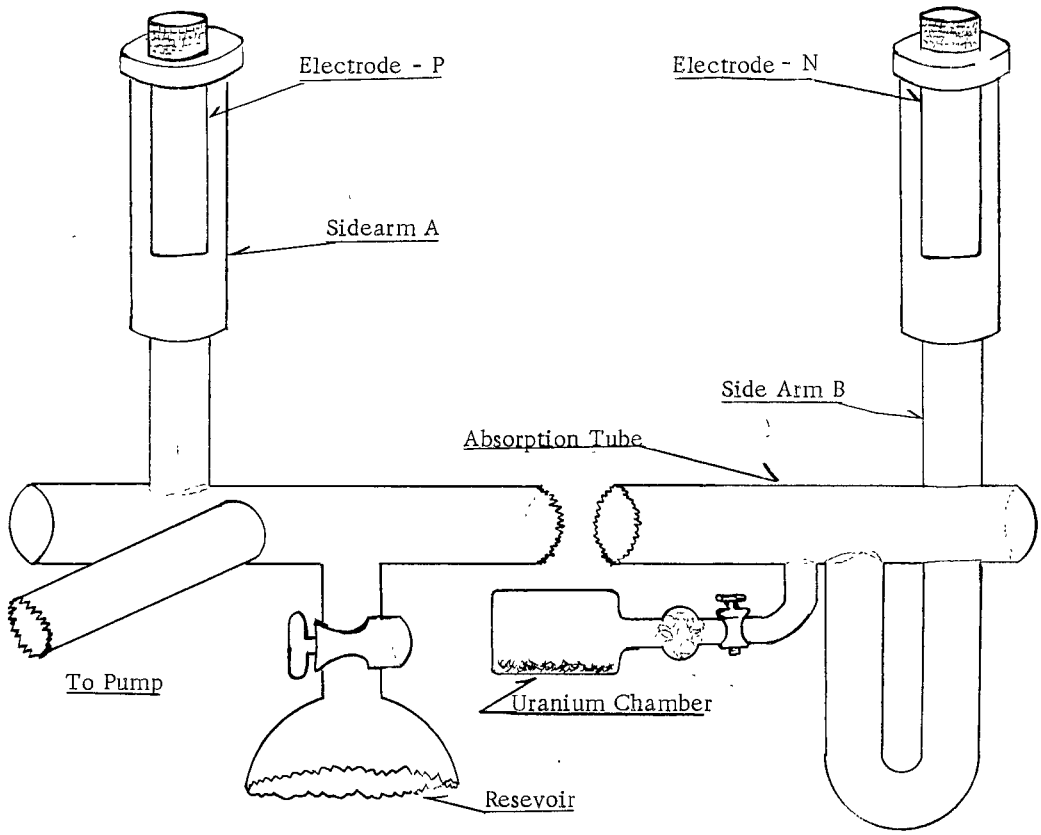
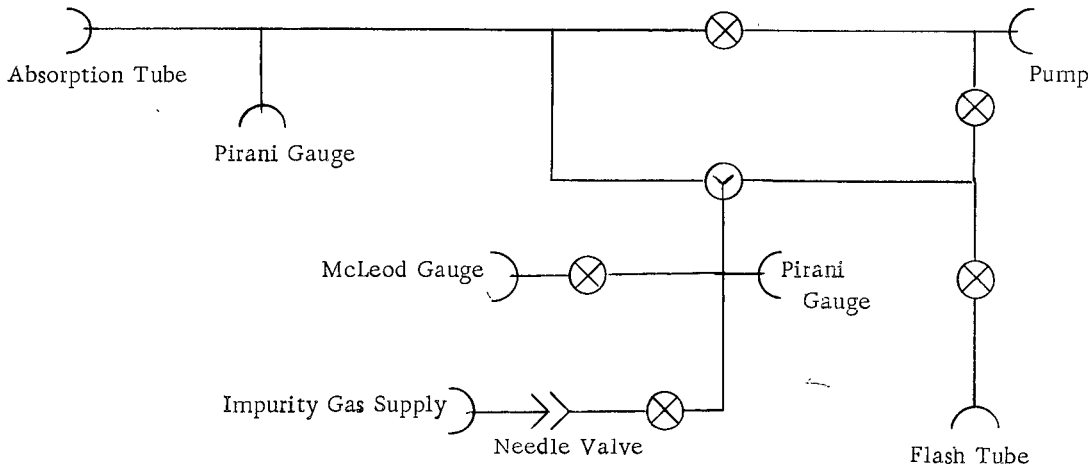


FIGURE 6 - WAVE FORMS

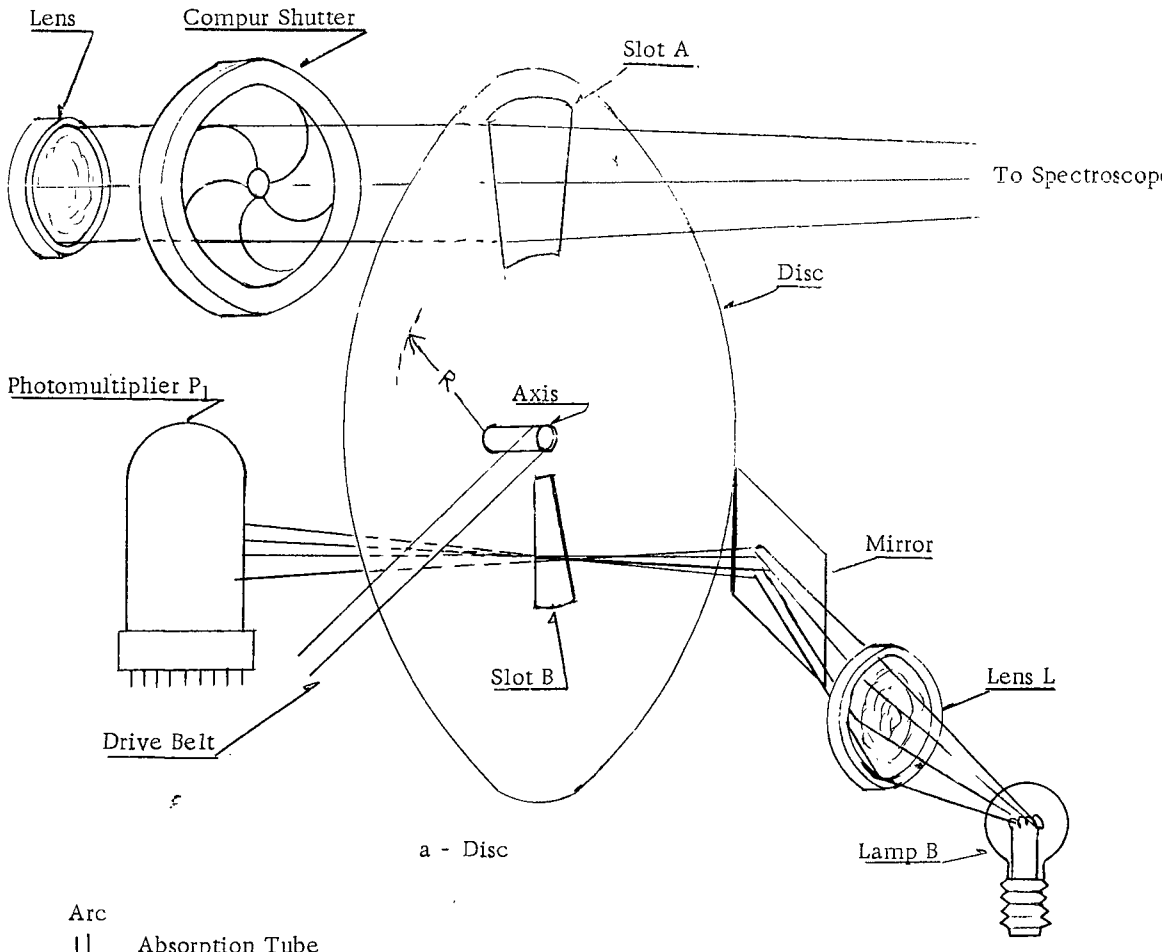


a - Absorbtion Tube

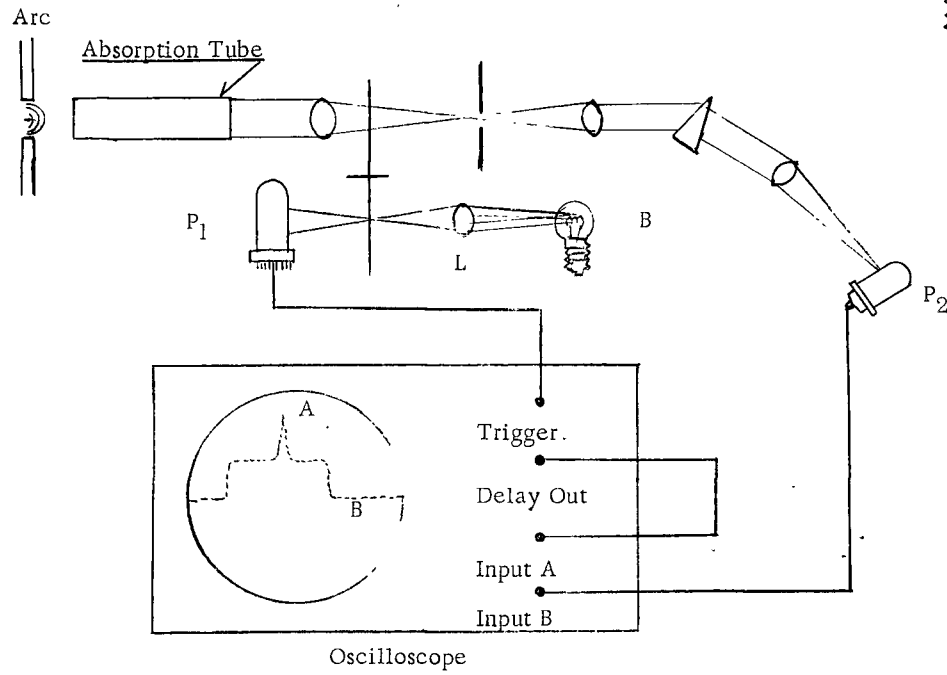


b - Flow Scheme

FIGURE 7 - PLASMA UNIT



a - Disc



b - Synchronization

FIGURE 8 - SHUTTER UNIT

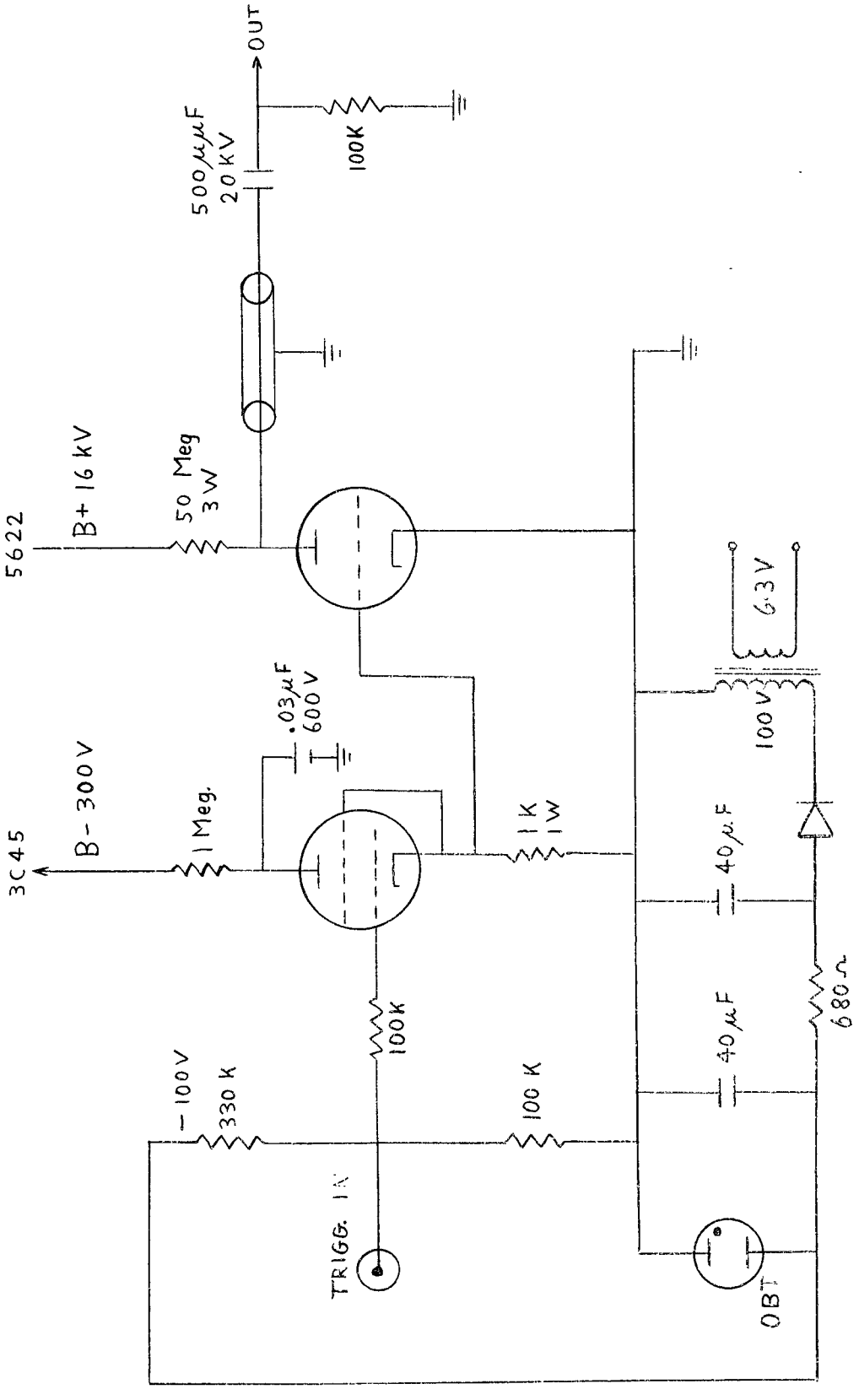


FIGURE 9 -HIGH VOLTAGE PULSE GENERATOR