CHAPTER II

EXPERIMENTAL SET UP.

2.1. Introduction

In this work experimental investigations and theoretical interpretation on the properties of magnetoplasma have been carried out. We have measured the parameters of positive column of discharges in magnetic field by different methods. To study the effect of magnetic field, a low pressure plasma with a low input power is desirable. In a low pressure discharge, as the mean free times of the plasma particles become larger, plasma transport properties will be affected more by the magnetic field. In general the magnetic fields used in our experiments can effectively magnetise the electrons and ions may be considered to be uninfluenced by the field. Before any set of observations a steady state of the discharge was obtained, thereafter, magnetic field was introduced and the plasma properties were measured. Measurements were made on glow and arc discharges when either a longitudinal (axial) or a transverse magnetic fiald was present.

2.2. Discharge tubes

All the discharge tubes in which measurements were carried out were constructed of pyrex glass. For glow discharge measurements the tubes were fitted with brass (80% Cu, 20% Zn) and aluminium electrodes and for low pressure mercury arcs, the arcs were struck ~~in~~ between mercury pools. Two types of arc tubes were constructed - vertical and horizontal and the tubes were fitted to simple traps through standard joints as shown in Fig.2.1. In this way, the mercury vapour going out of the discharge tube could condense smoothly and could return to the tube. Otherwise, it was observed that mercury would condense in the joining rubber tubes and a mercury plug would be formed in the passage and thereby would disturb the vacuum system. The dimensional parameters of the discharge tubes and the electrodes used etc. for different measurements have been shown in Table 2.1.

The discharge tubes were thoroughly cleaned by chromic acid, pet-ether and distilled water and dried on the pump. Then the tubes were heat baked in an electric oven in the usual way. Finally the tubes were heated on the pump by passing currents for several days (and for several hours before each set of observations) to degas them. For removing the occluded gases from the electrodes, both the electrodes were used as cathodes alternately by reversing the currents

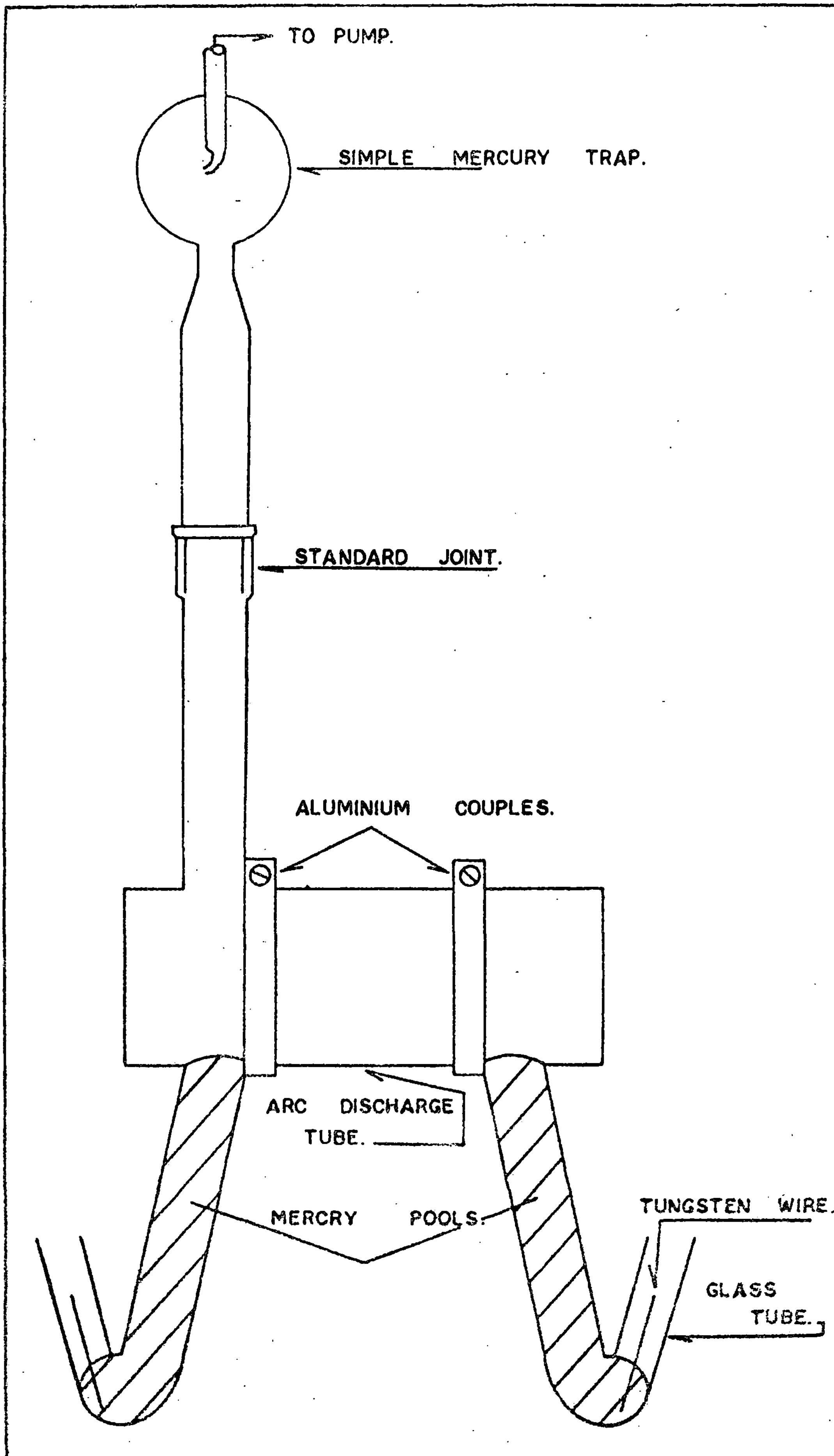

FIG. 2.1. A MERCURY ARC DISCHARGE TUBE.

through the discharge. The tubes were then flushed with the desired gas for two or three days and then the gas was introduced through a microleak of a needle valve to a desired pressure. The experimental set up of a typical experiment has been shown in fig. 2.2.

2.3. Preparation of gases

For measurements in dry air, the air was passed through two U-tubes containing phosphorus pentoxide powder and caustic potash pellets to remove traces of water vapour, then it was introduced to the discharge tube through a needle valve. Hydrogen and oxygen gases were prepared from electrolysis of a warm solution of pure barium hydroxide in between platinum electrodes in a U-tube. For hydrogen, the gas evolved from the cathode was passed through a hard glass tube containing copper spiral heated electrically. The gas was next passed through series of U-tubes containing phosphorous pentoxide powder and caustic potash pellets. The oxygen gas, evolved in the anode of the electrolysis tube was passed through a flask containing concentrated sulphuric acid. The nitrogen gas was supplied by Indian Oxygen Limited and was passed through concentrated sulphuric acid. After purification has been done in the stated manners the gases were stored in a round bottomed glass flask which is connected to the discharge tube. For measurements in the glow discharges in transverse

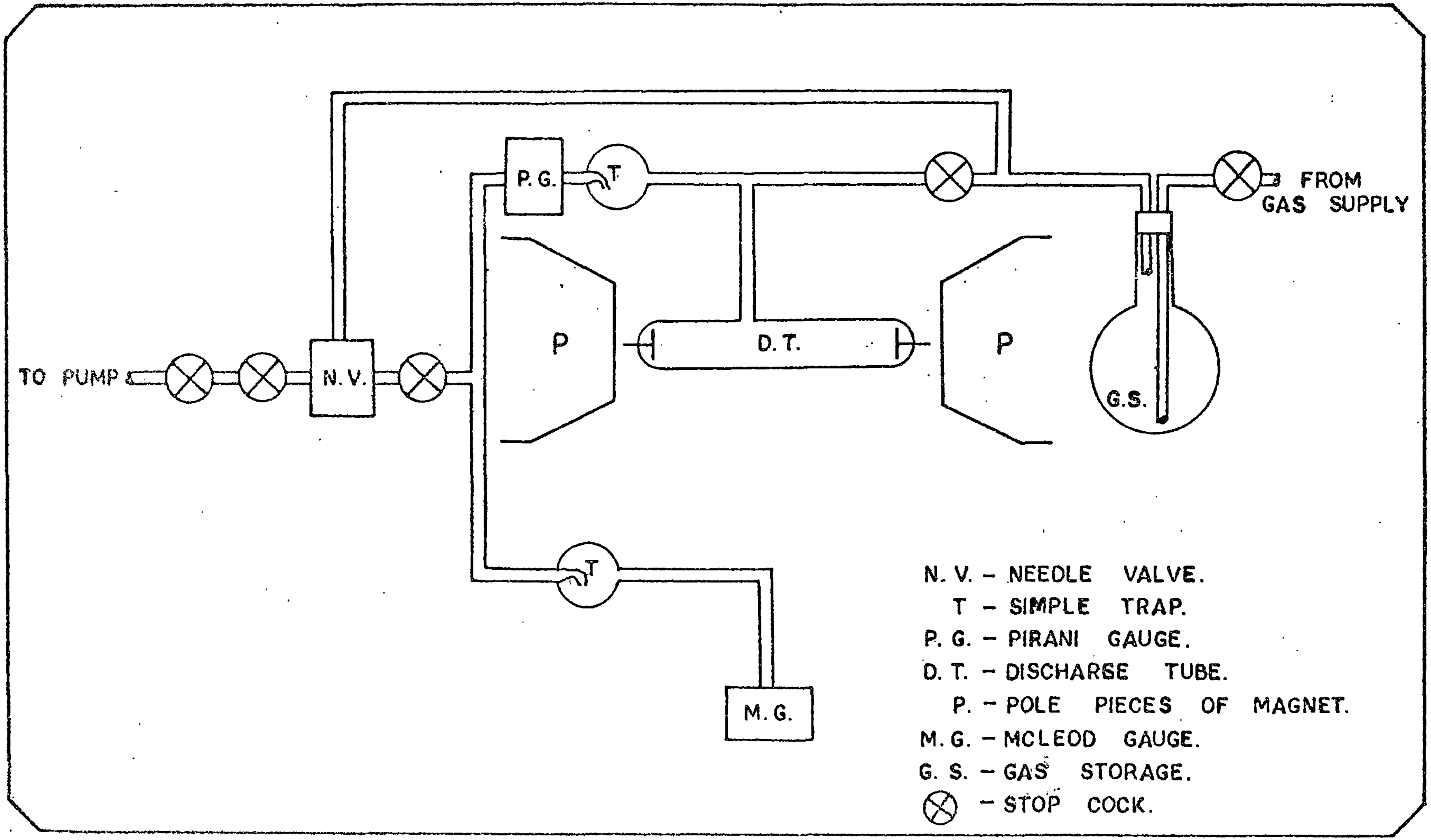

FIG. 2.2.

Fig. 2.2. An experimental set up in longitudinal magnetic field.

TABLE 2.1

Dimensional parameters and other characteristics of the discharge tubes.

Experiments with reference to chapter number.	Dimensions of discharge tubes			Electrodes used and electrode seperation.	Remarks.
	Innder diameter (cm)	length (cm)	Thickness of the tube wall		
1. Probe measurements in transverse magnetic field (Chap.III)	4	22	≈ 0.1 cm.	brass 16.9 cm.	
2. Probe measurements in longitudinal magnetic field(Chap.III)	2.5	8.5	≈ 0.1 cm.	brass 5.5 cm.	
3. Measurement of electron temperature of glow discharge in transverse magnetic field(Chap.IV &V)	1.5	19.5	≈ 0.1 cm	aluminium 17.5 cm.	at the central region, the tube is constricted with diameter appx. 0.5 cm.
4. Measurements of plasma parameters of low pressure mercury arc in longitudinal magnetic field (Chapter VI and VII)	1.5	8	0.14 cm.	mercury pools ≈ 7 cm.	vertical discharge tubes.
5. Investigations on glow processes of low pressure mercury afterglow in axial magnetic field (Chapter VIII)	3.6	9	0.17 cm.	mercury pools ≈ 7 cm.	horizontal tube fitted with two aluminium couplers for r.f. voltage supply.

magnetic field by spectroscopic method, the discharge tubes filled with hydrogen and helium gas at a pressure of one torr was supplied by a supplier. For the usual discharge tubes, after several days of run for outgasing and observation purposes, the glass wall would become coated by impurity materials due to sputtering of the cathode. In this way, these tubes could not be used for spectroscopic measurements, so built-in tubes with aluminium electrodes were preferable. The tubes were constricted in the central portion where magnetic field was applied. The constriction greatly enhanced the radiation output. In the spectrum, no lines of considerable intensity (in the visible region)of any impurity material was observed.

For mercury arcs, triple distilled mercury was used. In course of experiments, occassionally the mercury in the tubes was replaced by fresh supply and the discharge tubes were cleaned and degassed.

2.4. Measurements of pressure

~~Rkx~~ Pressure of the gas in the discharge tube was measured by a Mcleod gauge filled with triple distilled mercury. It has been shown in fig. 2.2 that pressure in the discharge tube could not be measured directly because the tube was placed in between the pole pieces of electromagnet, but a parallel line was used. At the junction between these two vacuum lines the pressure is the same and if the conductance of the two lines are identical, the pressure in the discharge tube would be equal to that at the Mcleod gauge. Dushman and Lafferty (1962) have discussed that effective pumping speed, S_{eff} is given

$$\frac{1}{S_{eff}} = \frac{1}{S} + \frac{1}{C} \tag{2.1}$$

where S is the speed of the pump (50 litres/min) and C is the total conductance of the line. For viscous flow, conductance of a line is given by

$$C = 2 \cdot 84 \frac{a^4}{l} P_2 \quad \text{litre/sec} \tag{2.2}$$

where a and l are the radius and length of the tubes and P_2 the upstream pressure. So the parallel lines as shown in fig. 2.2 were identical as far as possible. The lines were made of rubber and polythene pressure tubes. For the same reason, the needle valve was placed in between the junction of identical lines and the pump. A pirani gauge was used in the discharge tube line and through it the pressure of air could be compared. For built-in glow discharge tubes, the pressure was stated to be one torr.

The pressure of mercury vapour was determined from standard tables (Hodgman, 1956) after noting the inside wall temperature (T_W) of the discharge tube which is equal to the outside wall temperature increased by the temperature drop over the tube wall resulting from the energy which is dissipated in the tube and carried away via the tube wall (Verweij, 1960). The outside wall temperature was measured by a mercury in glass thermometer when the arc was in a steady state. Generally the arcs were cooled by electric fans. So a steady state of an arc corresponded to a steady outer wall temperature. The temperature drop as calculated by Verweij can be estimated by assuming that the total energy dissipated $W = Ei$ per cm. of tube length (E is the intensity of electric field, measured by noting the voltage across the arc minus standard cathode fall of 10 volts as determined by Lamar and Crompton (1931), then devided by arc length and i is the arc current). This energy is carried away by thermal conduction through the surface area of 1 cm. of tube length, thus through $2\pi R$ cm^2 (R = internal radius of the discharge tube), since the amount of energy which escapes as radiation through the tube wall is relatively small, the ultraviolate resonance radiation being absorbed within a very small penetration depth in pyrex glass wall. The temperature drop ΔT_W is given by

$$W = 2\pi R K \frac{\Delta T_W}{d} \qquad (2.3)$$

where d is the thickness of glass wall (0.14 cm) and K is the thermal conductivity of the glass (K pyrex = 11×10^{-3} joule/cm/sec/°C). For a typical operation of arc at a current of 2.5 amp., ΔT_w amounted to 7-8°C. A plot of saturated vapour pressure of mercury (p_{Hg}) with T_w has been shown in fig. 2.3. Since number density of ground state mercury atoms n_g is directly related with p_{Hg} by the relation

$$n_g = 3.3 \times 10^{16} \frac{p_{Hg}}{T_w} 273 \qquad (2.4),$$

in fig. 2.3, n_g also has been plotted against T_w . In all of the arc measurements, dry air was admixed with mercury vapour. The pressure of dry air was measured by the Mcleod gauge.

2.5. Magnets and power supplies

In the experiments electromagnets were used. Depending upon the diameters and lengths of the discharge tubes, the diameter of the pole-pieces (10 cm. x 8 cm. square and 5 cm diameter) and length between them were adjusted. For a specific experiment, the pole-pieces were so chosen that the magnetic field was uniform and without any radial component at the location of discharge tube. For measurements in axial magnetic field, the total discharge tube was placed in between the pole-pieces as shown in

Was this checked? If so, how?

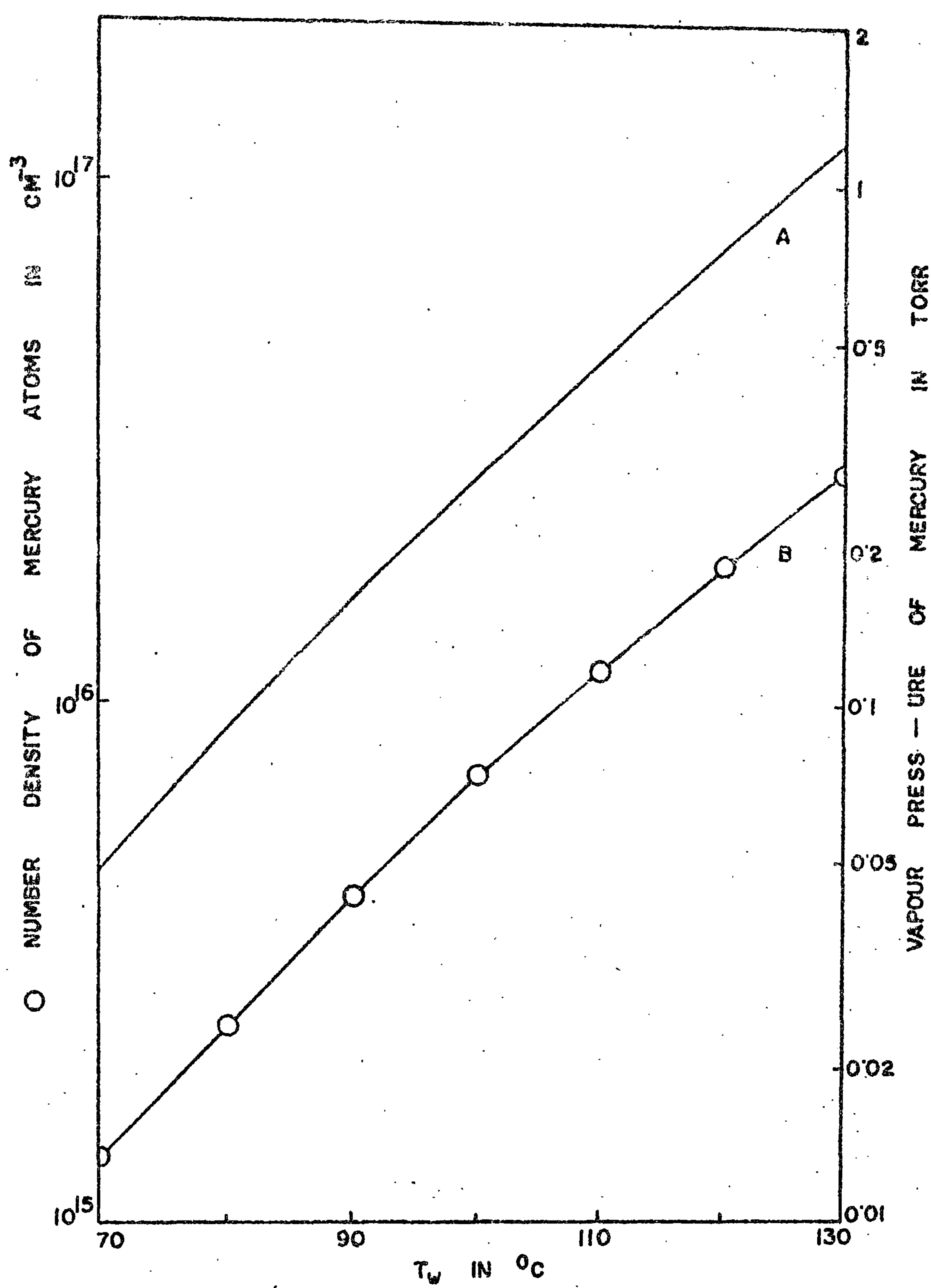

FIG. 2.3.

Fig. 2.3. Variation of vapour pressure and number density of mercury atoms with temperature of outer wall (T_w) of the discharge tube.

fig. 2.4, when a transverse magnetic field was used only a portion of positive column of the discharge where measurements were carried out, was placed in between the pole-pieces (fig. 2.5 (b)).

The magnetic fields were measured by a calibrated differential gauss meter. The electromagnets were powered by a stabilised d.c. supply.

The power supply for generating glow discharges, was a stabilised electronic d.c. supply (0 - 1200 volts in steps of 105 volts). The circuit for construction of the power supply was taken from Radio Amateur's Handbook (1965). The supply was connected to discharge tubes via a high wattage balast resistor (fig. 2.4). For a.c. glow discharges, 50 Hz common supply was used through a step up transformer whose input was connected to an auto-transformer. The mercury arcs were struck by a d.c. generator (200 - 240V.) whose voltage output could be adjusted to a constant value by an variable external resistor. For glow discharges, the discharge current was varied between 8 to 30 mA. and arc current was varied between 1.5 to 5 A.

2.6. Measurements of parameters of plasma with and without magnetic field by probe method

The parameters that were measured are electron temperature and axial electron density of the discharge. A cylindrical Langmuir probe of 0.019 cm. diameter was inserted

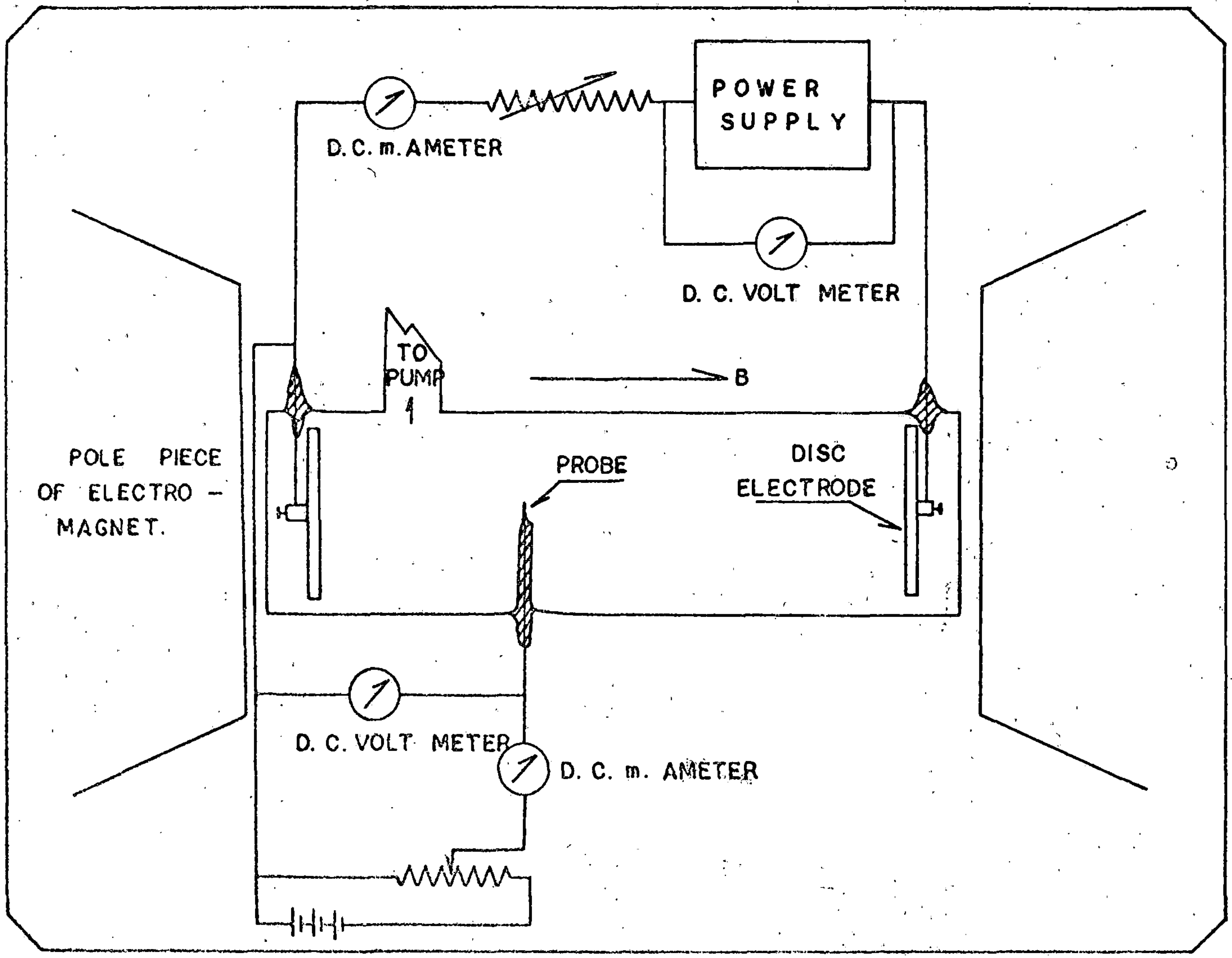

FIG. 2.4.

Fig. 2.4. Probe circuit and discharge tube circuit.

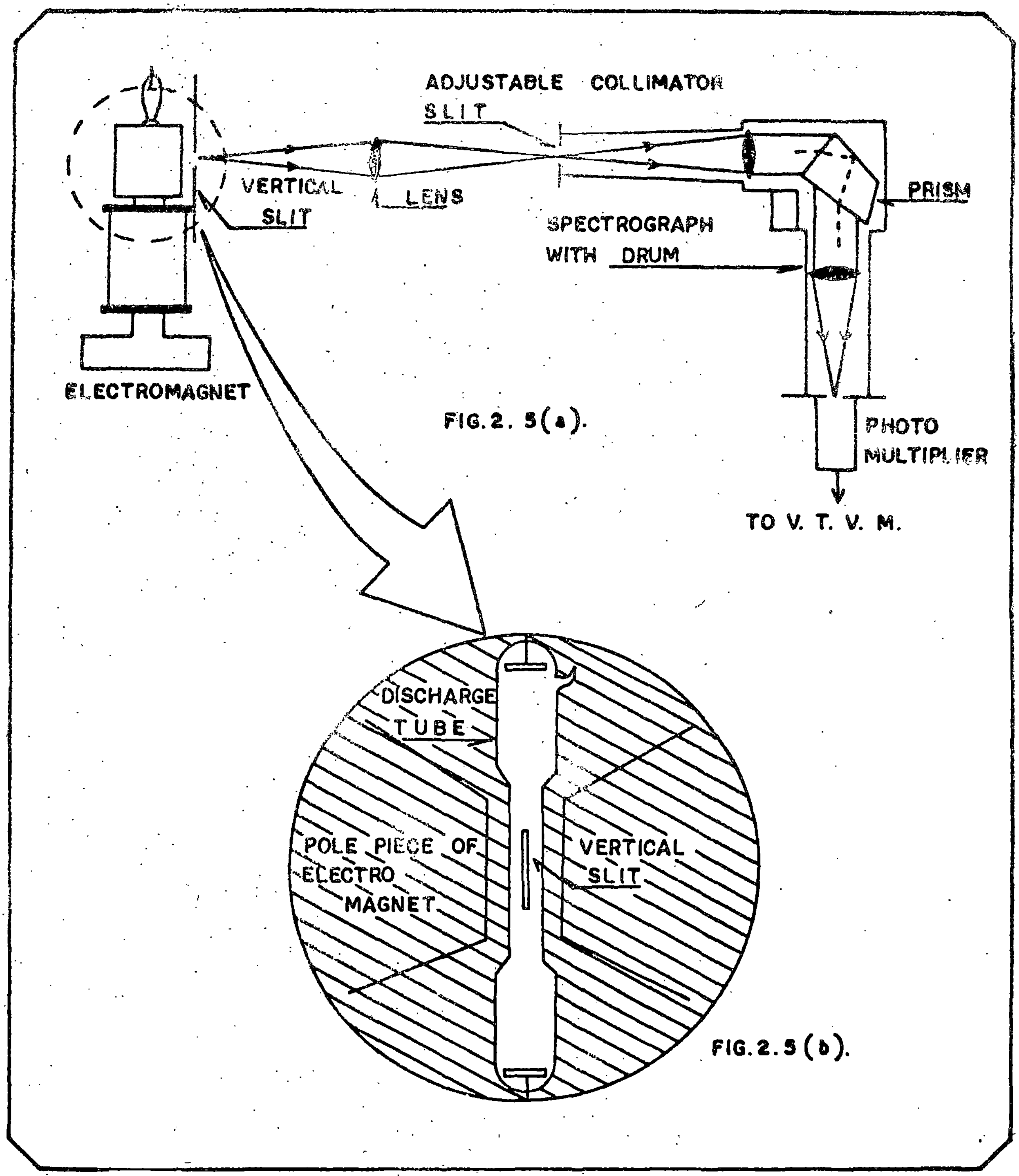

Fig. 2.5. Experimental set up for spectroscopic measurements.

in the discharge tube through a glass jacket. The material of probe was tungsten. The center of the probe was placed at the axis of the discharge tube and the probe was perpendicular to the axis and also to the magnetic fields when used. Generally the length of the probe (l) should be much larger than radius (r_p) of the probe. But an upper limit of the ratio l / r_p may be determined from the expression of electron saturation current to the probe

$$I_{e\,sat} = -n_e e A_p \left(\frac{T_e}{2\pi m}\right)^{1/2} \qquad (2.5)$$

where n_e , T_e , m and e are the number density, temperature, mass and charge of electrons and A_p is the probe collection area, $A_p = 2\pi r_p l$. $I_{e\,sat}$ is desired ~~as~~ not too large so that probe would not become too hot (or incandescent) and damaged as a consequence of the energy delivered at the probe by the electron current. We utilised a 4.1 mm. long probe placed at a distance 2.5 cm. away from the anode for measurements in transverse magnetic field. For a tube of diameter 4 cm. l/r_p was nearly 43 and for measurements in longitudinal magnetic field the probe was 2.2 mm. long and placed 1.3 cm. away from the discharge, so that $l/r_p \approx 23$ for a tube of diameter 2.5 cm. r_p was measured by a micrometer screw gauge and l by a travelling microscope. In this way the electron density that was determined was not exactly the value at the axis but an average corresponding to l . It will be shown in Chapter III that for the probes of these characteristic dimensions in practically all of the investigated discharges, the electron attraction characteristics may be interpreted according to orbital motion theory.

The probe measuring circuit has been shown in fig. 2.4. The probes were biased with a d.c. dry battery through a potentiometer. The most important probe current was recorded by a Philips PM 2403 electronic multimeter which has a minimum of full scale deflection for a current of 1 μ A. Another advantage of this particular meter is that an automatic polarity reversal technique is built-in. So external polarity reversal was not necessary for going from ion current to electron current and a polarity reversal indicator meter clearly indicates the exact point of reversal. The other point of the probe circuit was connected to anode and the probe voltagex which is generally negative with respect to anode was varied in steps of 0.5 - 2 volts. The probe current, which was measured, was the total current through the probe. Electron current I_e was determined by subtracting ion current I_i from the total probe current

$$I_e = I_{tot.} + |I_i| \qquad (2.6)$$

The details of probe data analysis have been given in chapter III.

2.7. Diagnostics by spectroscopic method

Spectroscopic method was utilised to determine electron temperature in both types of magnetic fields. In the investigations, the experimental set up was the same. A schematic diagram of the experimental set up has been ~~shw~~ shown in fig. 2.5 (a). The radiations from the axial regions of vertical discharge tube placed in between the pole pieces of the magnet after passing through a vertical slit was focussed by a double convex lens on the vertical slit of the collimator of the spectrograph. In the spectrograph, there was a Pellin-Broca prism for 90 degree deflection of the spectrum. Such a mounting was appropriate as a monochromator with fixed slit. The exit slit was in a direction 90 degree with the plasma source. The wavelength is changed by rotating the prism with a mechanical arrangement fitted with an accurately calibrated drum. The wavelengths of the radiations were further checked from standard values given in International Critical Tables (1926). Generally, this type of apparatus has a low resolving power which would be advantageous in our investigations and this will be discussed in Chapter IV. The slit width which could be varied with a micrometer arrangement, was varied from 0.25 mm. to 1 mm. depending on the response of lines chosen to the photomultiplier. For a set of observation however, the slit width was fixed. For measuring T_e , two criteria for suitable line choice may be mentioned:

(i) The energy of seperation of the upper states of the two transitions chosen should be comparable to the value of T_e . But this was not possible always. For two lines in the visible region which had sufficient response to the detector the energy of seperation of upper states some times became smaller than the value of T_e . One of the remedies that is suggested is to use one of the ionic lines and one atomic line. But in magnetic field the intensities of atomic and ionic lines vary differently. The reason behind is that atomic lines are determined by T_e and n_e which is affected by magnetic field, whereas for ionic lines, the radiation would be affected by magnetic field through T_e , n_e and n_i . Moreover no sufficiently strong ionic line was observable in the discharges investigated.

(ii) the lines should be such that in the near vicinity there would be no other line, so that $\int_0^\infty I_\nu \, d\nu$ is the measure of total intensity of a radiation with frequency ν and in our investigation slit-widths were comparatively wide enough so as to detect the total intensity of radiation.

The collimator was focussed by rack and pinion arrangements, the selected line was focussed on the cathode of the photomultiplier M10FS29V λ operated at 1425 V. The head-on type photomultiplier which has low mean radiation equivalence of dark current was placed in a darkened chamber behind the exit slit. The power source of photo multiplier was made in two sections: the first was 1200 V. stabilised pack to supply the dynode voltage while the second was used to furnish some 225 V. between the final dynode and the anode (fig. 2.6). The last voltage source was also used to operate the vacuum tube voltmeter, which consisted of two 6J7 tubes operating with about 32V. on the plates and about 1.3 V negative grid bias. The grids were connected to the two ends of the resistor R_1 (600 KΩ), which was in series with the plate of the photomultiplier tube. When current flowed through this resistor, a voltage drop occured and one of the 6J7 tubes drew less current producing an imbalance in the plate circuit. A 0-200 μA meter between the plates measured this imbalance.

When the signal approximated 3V, the 6J7 reached cut-off, and beyond this point there was no increase in the meter deflection. With no light on photomultiplier tube and a rough balance obtained with R_4, the meter was set to zero with R_2. In this way the effect of photomultiplier dark current was eliminated completely. Then, with 3V or more applied to resistor R_1, the meter was set to full scale deflection by means of control R_3. The micrometer at the out put recorded the intensity of the spectral line. The slit was adjusted so that meter deflection corresponding to the line with strongest response to the photomultiplier was well within the range of full scale deflection.

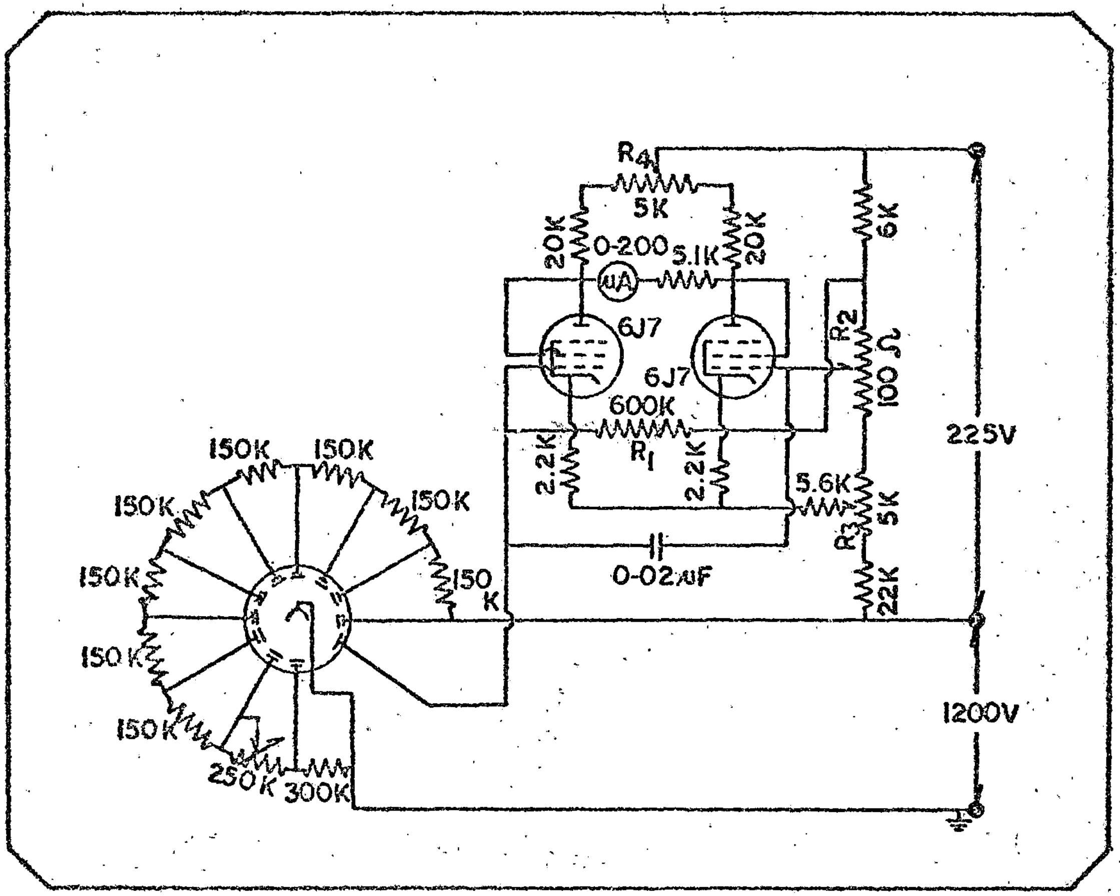

FIG. 2.6. PHOTOMULTIPLIER CIRCUIT.

The sensitivity of a photomultiplier depends on wavelength of incident radiation and on quantum efficiency of the cathode material (including the effect of photomultiplier's window material). Percentage Quantum efficiency of M10FS29V λ , taken from Carl Zeiss brochure No.40-637-2, has been reproduced in fig. 2.7. From this plot the cathode radiant sensitivity S in amperes per watt corresponding to a radiation of wavelength λ (Å) is calculated as

$$S = \frac{Q\,\lambda}{12395 \times 100} \qquad (2.7)$$

here Q is the percentage quantum efficiency. From S, the relative spectral sensitivity for two lines was calculated and the microammeter reading for total intensities of lines was corrected for relative spectral response of the photomultiplier. Moreover emission coefficient corresponding to a radiation with frequency ν which is directly proportional to observed total intensity can be seperated into a continuous and discrete part

$$\epsilon_{\nu} = \epsilon_{\nu,c} + \epsilon_{\nu,L} \qquad (2.8)$$

$\epsilon_{\nu,L}$, contains the desired spontaneously emitted energy within the line, $\epsilon_{\nu,c}$ was eliminated by balancing the V.T.V.M. to the null of meter reading with resistors in the circuit when the continuum radiations

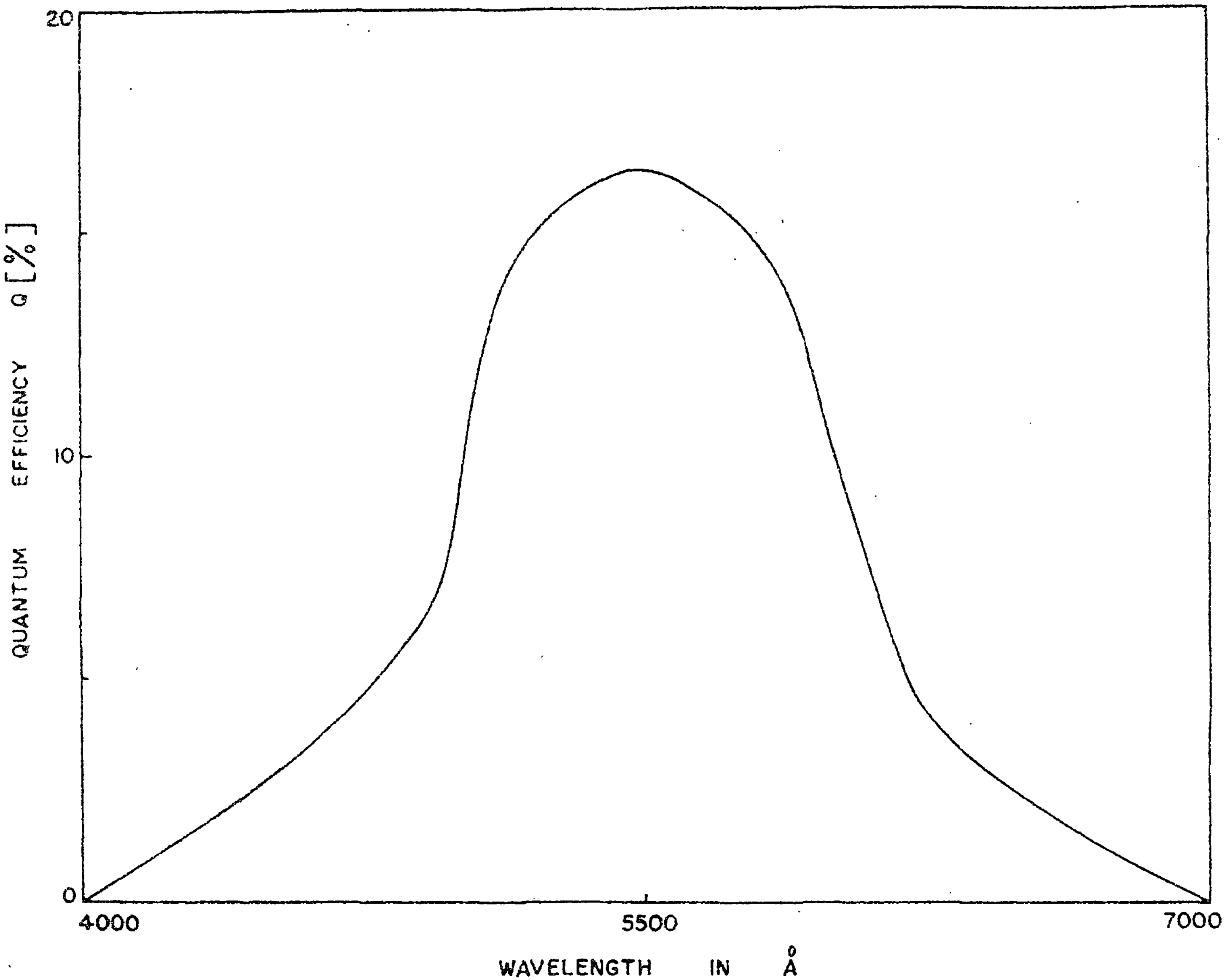

FIG. 2.7. QUANTUM EFFICIENCY IN % OF PHOTOMULTIPLIER MIOFS29Vλ (VEB CARL ZEISS JENA BROCHURE NO. 40-637-2.)

at the near vicinity of the line was focussed on the photomultiplier tube cathode and the contribution for $\epsilon_{\nu,c}$ was found to be negligible.

2.8. Measurements of variations of discharge current and voltage across a low pressure mercury arc in longitudinal magnetic field

The currents were recorded with 0-5A meter, connected in series with the discharge tube. A V.T.V.M. of internal resistance 35 MΩ was utilised to measure the voltage across the arc.

It was observed during the experiments that with time the arc voltage slowly and gradually increased. Cobine (1958) explained the phenomenon as due to continuous evaporation of ~~t~~ cathode surface by heating. ~~From~~ For evaporation of cathode, the positive column increases. As electric field in the positive column tries to remain constant, the voltage drop across the arc increases continuously. A measurement of this continuous increase of voltage with time showed that, fortunately, in the range of discharge currents in our experiments, this was a slow process. The arcs were vertical and the cathode was the lower mercury pool. Our intention was that the evaporated cathode material may be compensated by the condensed mercury that was returning to the lower pool by gax gravity. However, the measurements of variation of voltage and current with magnetic field were made rapidly enough so that the slower process as mentioned above may be neglected.

2.9. Measurements of persistence times of a mercury afterglow

Measurements of persistence times of a mercury afterglow (admixed with dry air) were carried out in a cylindrical discharge tube (details in fig. 21 2.1, table 2.1). As we are interested to study the behaviour of a recombining plasma with and without a magnetic field, the effect due to diffusion transport was lessened by taking a discharge vessel with comparatively large diameter and dry air was admixed to increase the pressure.

Two aluminium couplers clamped in the middle of the discharge tube from outside were connected to a Hartley oscillator to supply the radio frequency voltage. The couplers were were seperated by 2.35 cm. The level of r.f. power supplied by the oscillator was low enough so as tox not to cause a breakdown of the gas. A 6V6 xx vacuum tube was utilised as the oscillator. The r.m.s. voltage of the oscillator output was measured by a half wave rectifier made of 6H6 tube. The frequency was calibrated by a digital frequency meter. The measured r.m.s. voltages and frequencies corresponding to the dial readings of the condenser in the oscillator has been given in Table 2.2.

TABLE 2.2

r.m.s. voltage and frequency corresponding to condenser dial reading of the oscillator.

Dial reading	r.m.s. voltage of r.f. oscillator (volts)	frequency (MHz)
1.	91.0	-
5	96.0	0.594
10	100.0	1.068
15	100.5	1.338
20	105.0	1.364
25	120.5	1.464
30	120.0	1.583
35	122.5	1.623

During the experiments, the arc discharge was run for a few minutes, so that a steady condition was reached and T_W was noted. Then the primary arc discharge was switched off. Generally an afterglow persists for a ~~xxx~~ fraction of second. But due to the supply of r.f. power to the couplers, the glow persisted for longer time and then disappeared. When no r.f. power was supplied to the couplers, the afterglow did not persist and disappeared in a fraction of second as usually. The persistence times of the glow with rf power supplied were recorded by two stopwatches. The details of the measurement procedures have been discussed in chapter VIII. It will be discussed there that the decay processes (directly related to the persistence times) generally depends upon the temperature of the surrounding envidronment. So the persistence times were recorded in the same envidronment for a set and no forced cooling of the primary arc was made.

2.10. Possible sources of errors

It was observed that for a discharge system to be leakproof, degassed and stable, several days of continuour running was needed. Our desire was that the plasma would exhibit the same physical behaviour day after day dependent only upon some externally controlled dial setting. Unfortunately, the very nature of the plasma is a non-linear one - not restricted to a single unique operating mode. From this point of view, a stabilised discharge free from striactions and any other terbulence was desirable. Moreover, some times oscillations were visible in the plasma when a magnetic field was present. The oscillations were reflected in external measuring meters. These oscillations determined the upper limits of the magnetic fields used and below this limit the readings were acceptable. In probe method, the magnetic fields used were of comparatively low values. In spectroscopic method, the readings of the output μA meter which measured the total intensities of a lines were observed to be stable after six to eight hours of warming up of the V.T.V.M. circuit. Nevertheless some sources of errors may be identified. There are: pressures were not measured at the discharge tube, but a parallel vacuum line was used. For built-in discharge tubes, the pressures were stated to be one torr which could not be verified. Pressure of mercury vapour was determined by noting T_w at a point of the discharge tube. Moreover, in calculation T_w was assumed equal to gas temperature T_g and T_g was considered to be uniform across the tube cross section. As it was not possible for us to determine T_g at the axis, the above assumption was made.

The purify of the gases was not checked. But it was assumed that the gases utilised were free from impurities. Spectroscopic investigation however, did not reveal the presence of any other gas as impurity.

What about Hg contamination from the McLeod gauge

No correction was made either for possible contaminations of Langmuir probes or for changes of work function of comparatively hot probes. Moreover, the results obtained by a method could not be verified by another diagnostic method in the same condition of discharge.

Several other assumptions were also made in course of calculations and these will be discussed, subsequently.

References:

1. Cobine, J.D. (1958), Gaseous conductors: theory and engineering applications (Dover Publication, New York).

2. Dushman, S. and Lafferty, J.M. (1962) Scientific Foundations of Vacuum Techniques, 2nd. Edn. (John Wiley, New York).

3. Hodgman, C.D. (1956), Hand Book of Chemistry and Physics, 38th. Edn. (Chemical Rubber Publishing Co., Ohio).

4. International Critical Tables of Numerical Data (1926), Vol.5 (McGraw Hill Book Co., NY).

5. Lamar, E.S. and Compton, K.T. (1931) Phys. Rev. 37 1069.

6. Radio Amateur's Hand Book (1965), 42nd.Edn. (American radio relay league, West Hartford).

7. Verweij, W. (1960), Philips Res. Rep. Suppl. No.2.