

"SPECTROSCOPIC STUDIES OF HYDROGEN PLASMAS
IN A MAGNETIC WELL"

A Thesis presented in partial fulfilment of the requirements for the degree of M.Sc. in Physics at the University of Cape Town, Rondebosch, Cape.

Douw G. Steyn

May 1970

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A B S T R A C T

Experiments are described in which the containment times of plasmas in Andreoletti's modified theta-pinch apparatus are increased by the addition of an external D.C. field produced by a modified version of the "Tennis Ball Seam" conductor described by Larkin.

The diagnostics used are all spectroscopic.

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CHAPTER I

INTRODUCTION

CHAPTER I

The plasma dynamics of plasmas trapped in a magnetic well described by Andreoletti (reference I-1) have been studied using magnetic probes (reference I-2). These studies showed serious leaks. The present experiments are attempts at curing these leaks using a single loop conductor to produce a D.C. magnetic well superposed on the spire field (operating in the A.C. mode). The single loop conductor is a modified version of the "Tennis Ball Seam" described by Larkin (reference I-3).

The plasma parameters are determined spectroscopically, the electron density being calculated from the measured half width of H_{β} , and the electron temperatures from the measured intensity ratios of the Helium lines He_{II} (4686) and He_I (5875).

CHAPTER II

APPARATUS

CHAPTER II

1. ELECTRICAL SYSTEMS

Main Capacitor Bank.

The main compression discharge in the experiments was provided by a capacitor bank consisting of 12, 8.5 μF capacitors connected in pairs. As shown in diagram II - 1, the capacitors were charged in parallel through the charging resistors, and discharged in series-parallel through the load coil by the trigatrons (diagram II - 2). This is identical to the voltage-doubling system used by Kemp et al (Reference II - 1). The leads i and ii in diagram II - 1 were 10, 2 ft lengths of 50 Ω , 70 nH/foot co-axial cable. Leads iii were 10, 10 ft lengths of the same cable.

Another capacitor unit (a pair identical to the main bank capacitor pairs) was set up in the circuit and used to provide a preheater discharge.

The output leads from the main and preheater banks (70 co-axial leads) were connected to collector plates made from $\frac{3}{16}$ " brass sheeting insulated by 6 sheets of .006" Melinex sheeting. The output ends of these collector plates were bolted onto the load coil (diagram II - 4) which was constructed out of 12 gauge copper sheeting, silver-

soldered at the edges. The connecting bars in the axial plane were to facilitate removal of the vacuum chamber.

A crowbar trigatron set in the collector plates will be described in a later section.

Table II - 1

<u>Bank Parameters</u>	
Total Capacitance (discharge)	25.5 μ F
Capacitor Inductance	90 nH/cap (1)
Switch Inductance	22 nH/switch (2)
Load Inductance	65 nH (3)
Total Inductance in uncrowbarred discharge	120 nH (4)
Period of uncrowbarred discharge	10.5 μ sec
Charging Voltage	12 kV
Total stored Energy	7.3 kJ
Peak Current through Load -	
Uncrowbarred	220 kA (5)
Crowbarred	150 kA

- (1) The manufacturer's specification sheets give the capacitor ringing frequency as 180 kc, this leads to an inductance of 90 nH/cap.
- (2) This figure is an estimate based on an approximate calculation which assumes each switch to be a section of

a co-axial cable with the same dimensions. The switch inductance was also measured in a discharge experiment giving rise to a similar result.

- (3) This figure was obtained by subtracting the calculated (approximate) bank inductance

$$L_B = \frac{1}{6} [2(L_{\text{cap}} + L_{\text{switch}}) + \frac{1}{10} (L_{10, \text{ cable}}) + \frac{2}{10} (L_{2, \text{ cable}})] \\ = 53.6 \text{ nH}$$

from the measured total induction (see below).

- (4) This was calculated from oscilloscope traces of the current from two discharges, using the ratios of successive maxima, the period of the discharge and the rated capacity of the bank to solve simultaneously for the resistance and inductance.

$$L_{\text{total}} = 119.5 \text{ nH}$$

$$R_{\text{total}} = 3.92 \times 10^{-2} \Omega$$

- (5) The current traces shown in diagram II - 6 were calibrated from the amplitude of the 1st maximum in the uncrowbarred discharge which was given by :

$$I_{1\text{st max}} = \frac{V_0}{\omega L} e^{-Rt/L}$$

$$\text{where } R = 3.92 \times 10^{-2} \Omega$$

$$V_0 = 24 \text{ kV}$$

$$L = 119.5 \text{ nH}$$

$$t = \tau/4 = 2.63 \text{ sec}$$

$$\omega = 5.96 \times 10^5 \text{ sec}^{-1}$$

This gives $I_{1\text{st max}} = 219.05 \text{ kA}$.

Trigger Unit.

The trigger pulses (A and B in diagram II - 1) were supplied by a small capacitor bank switched through pulse transformers by a trigatron identical to the main bank trigatrons (diagram II - 3). The pulse circuit is shown in diagram II - 2. The main bank and preheater trigatrons were kept pressurised (nitrogen under 10 lbs/sq in) as they tend to become fouled with a hygroscopic salt (probably CuNO_3) after many discharges in air. Pulse C in diagram II - 1 was provided by an identical unit, but was fired independently at a different time to A and B.

Diagrams II - 1/2/3/4

DIAGRAM II-1

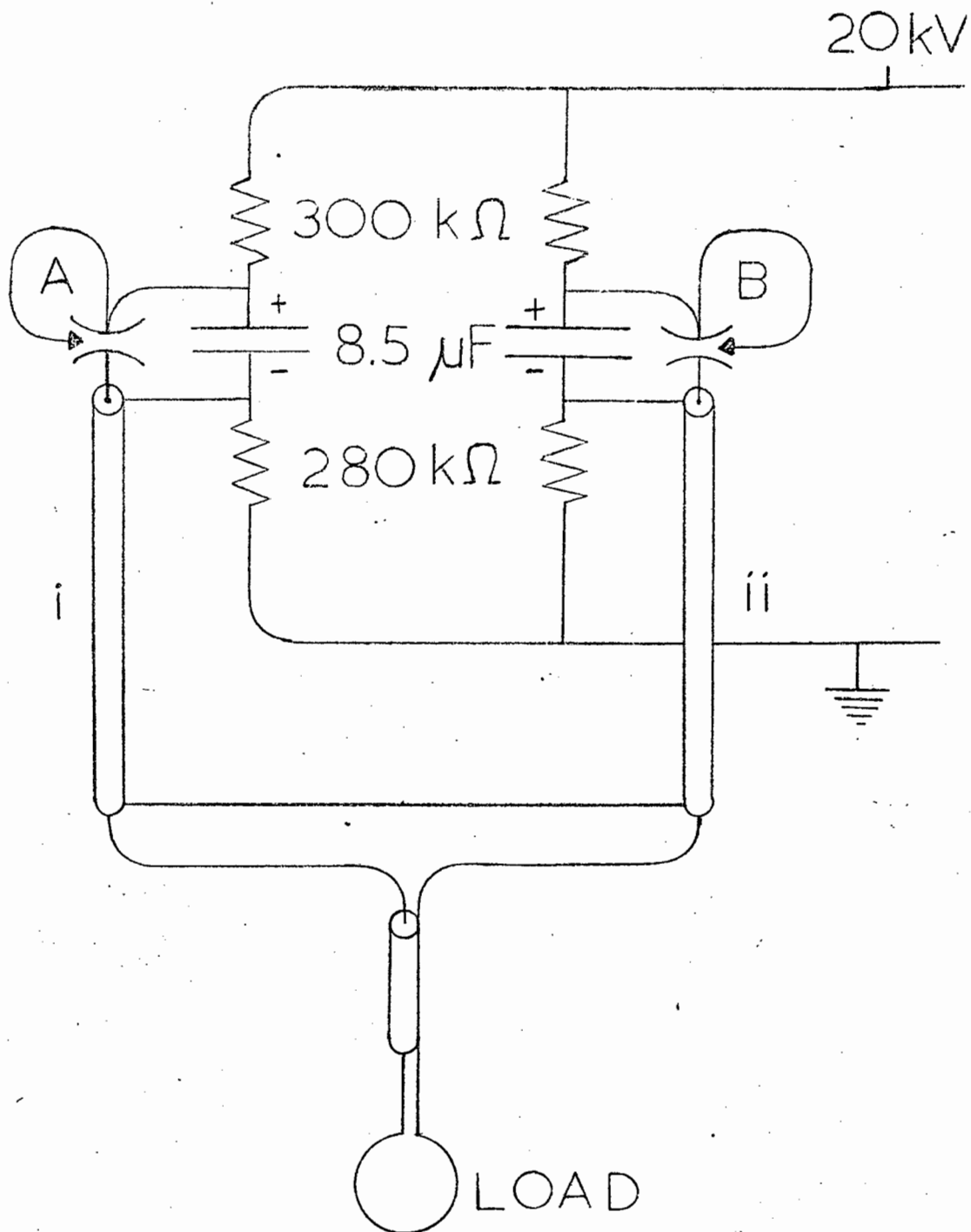


DIAGRAM II-2

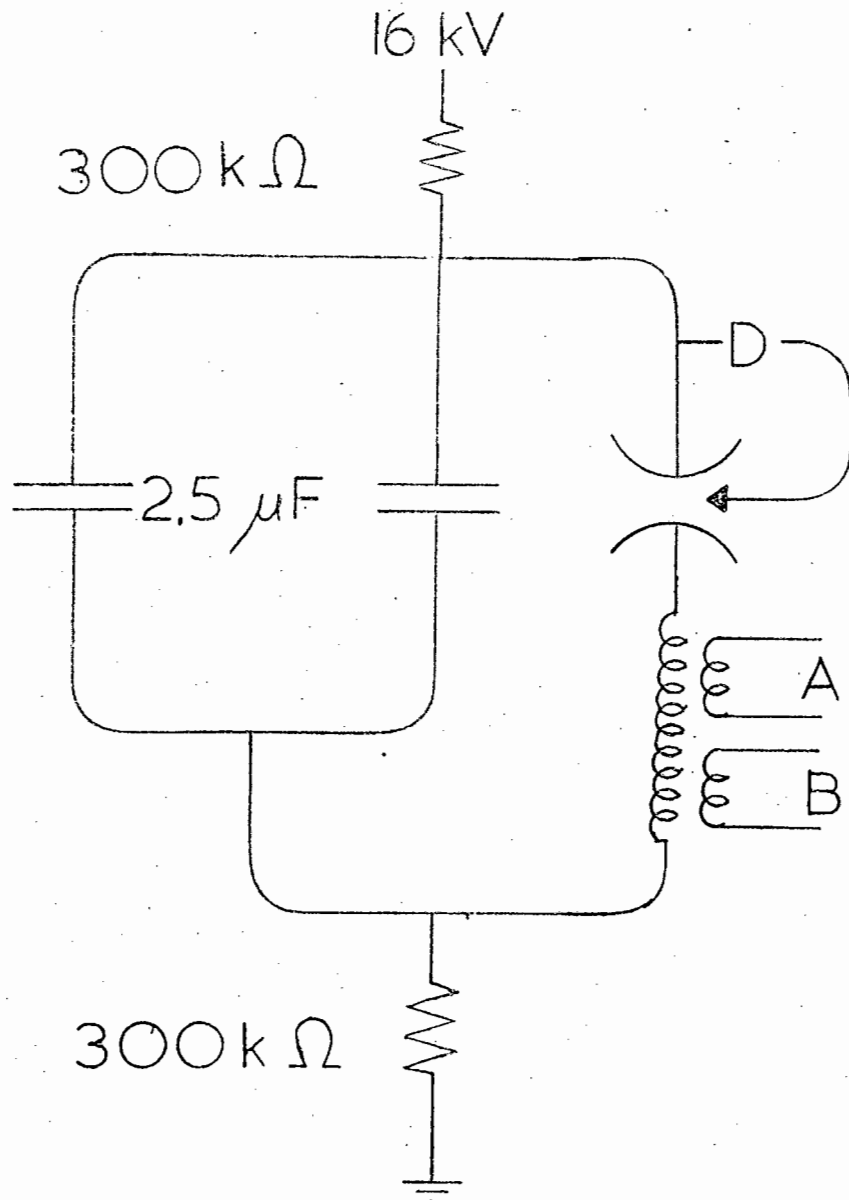


DIAGRAM II-3
SCALE 1:1.3

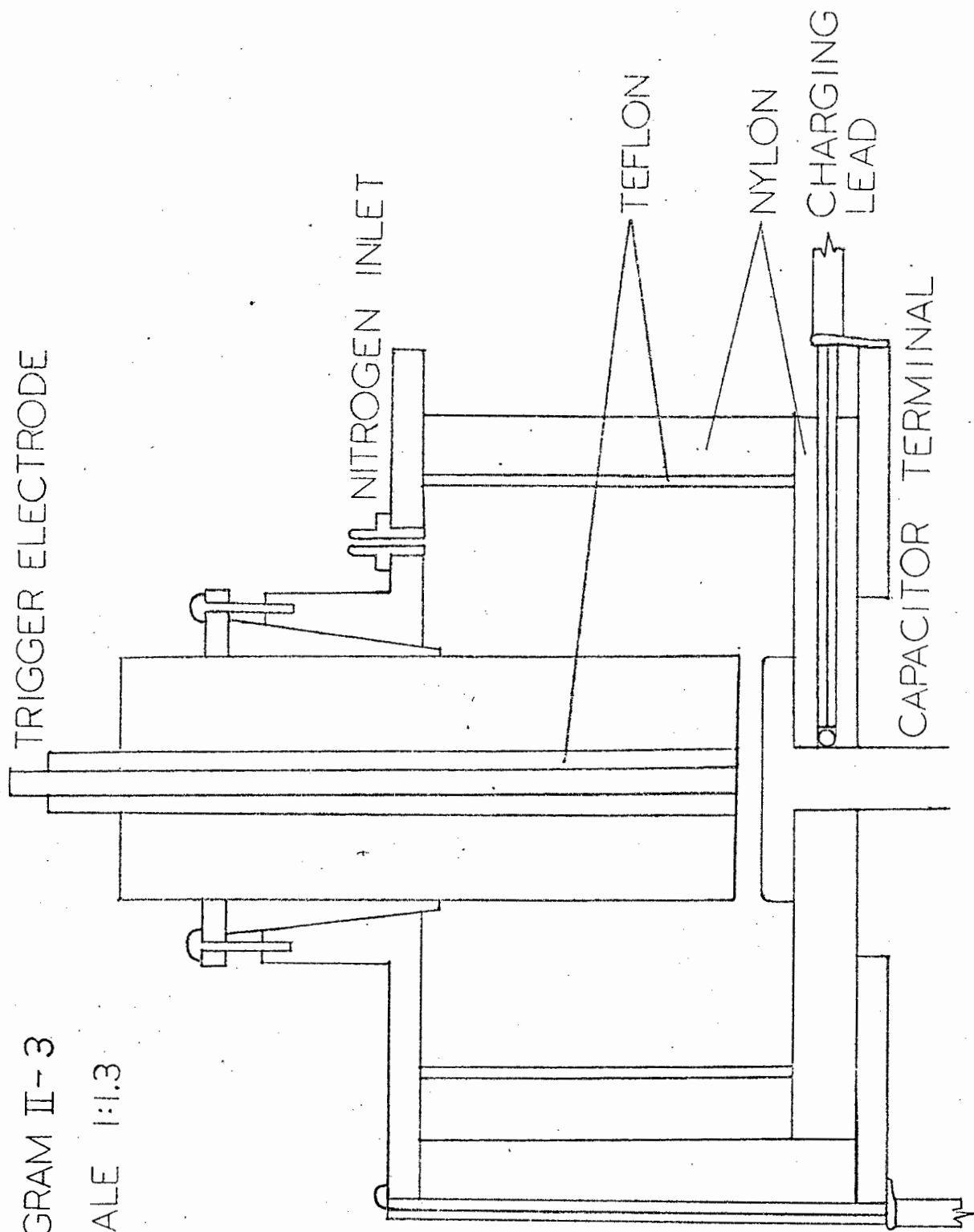
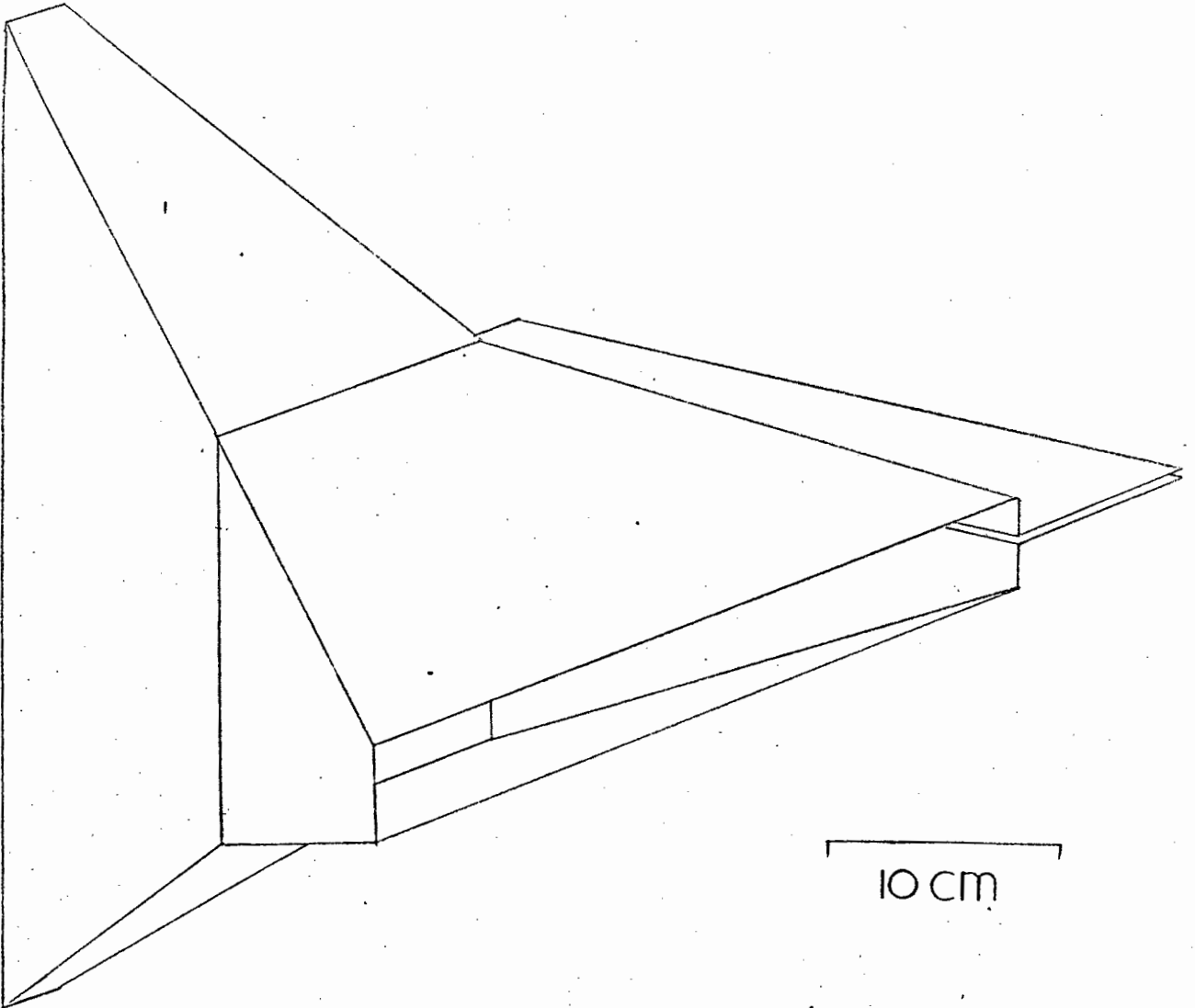


DIAGRAM II-4

TETRAHEDRAL SPIRE



Main Bank Crowbar.

Since the experiments were basically containment studies, an oscillatory discharge was necessarily unsuitable for the confining field, but a fast-rise field for the initial compression was necessary in order to prevent the compression field from penetrating the preheater plasma. Oscillatory discharges also have the big disadvantage of allowing the plasma to expand at the current zero and dislodge impurities from the walls of the container.

The required current, fast-rise and high, reasonably constant level, was obtained by crowbaring the discharge at the first current maximum. Ideally this would result in a current pulse having the same peak value and rise-time as the oscillatory discharge, and decaying exponentially. The decay time was given by the switch and load resistance and inductance.

The discharge was crowbarred by short circuiting the load through a large trigatron in the collector plates. This trigatron had to be fired when all the bank energy had been transferred into the magnetic fields in the load coil. This of course being when the voltage between the plates was zero. With this zero potential difference between the electrodes, the spark gap would not break down, so it was found best to trigger the gap just before the voltage reached zero. This resulted in the crowbarred current

maximum being about 70% of the possible maximum.

To keep the crowbar working reproducibly, the electrodes had to be cleaned and reset every 100 discharges (about). The Teflon insulator between the top electrode and the trigger electrode disintegrated at an alarming rate and also had to be checked regularly.

An estimate of the decay time of the crowbarred discharge can be obtained quite easily by assuming the switch resistance to be the same as that of the main bank switches which was $6 \times 10^{-2} \Omega$ per switch, assuming 50% of the bank resistance to be in the switches. This leads to a decay time of

$$\tau_D = \frac{2(L_C + L_L)}{R_C + R_L}$$

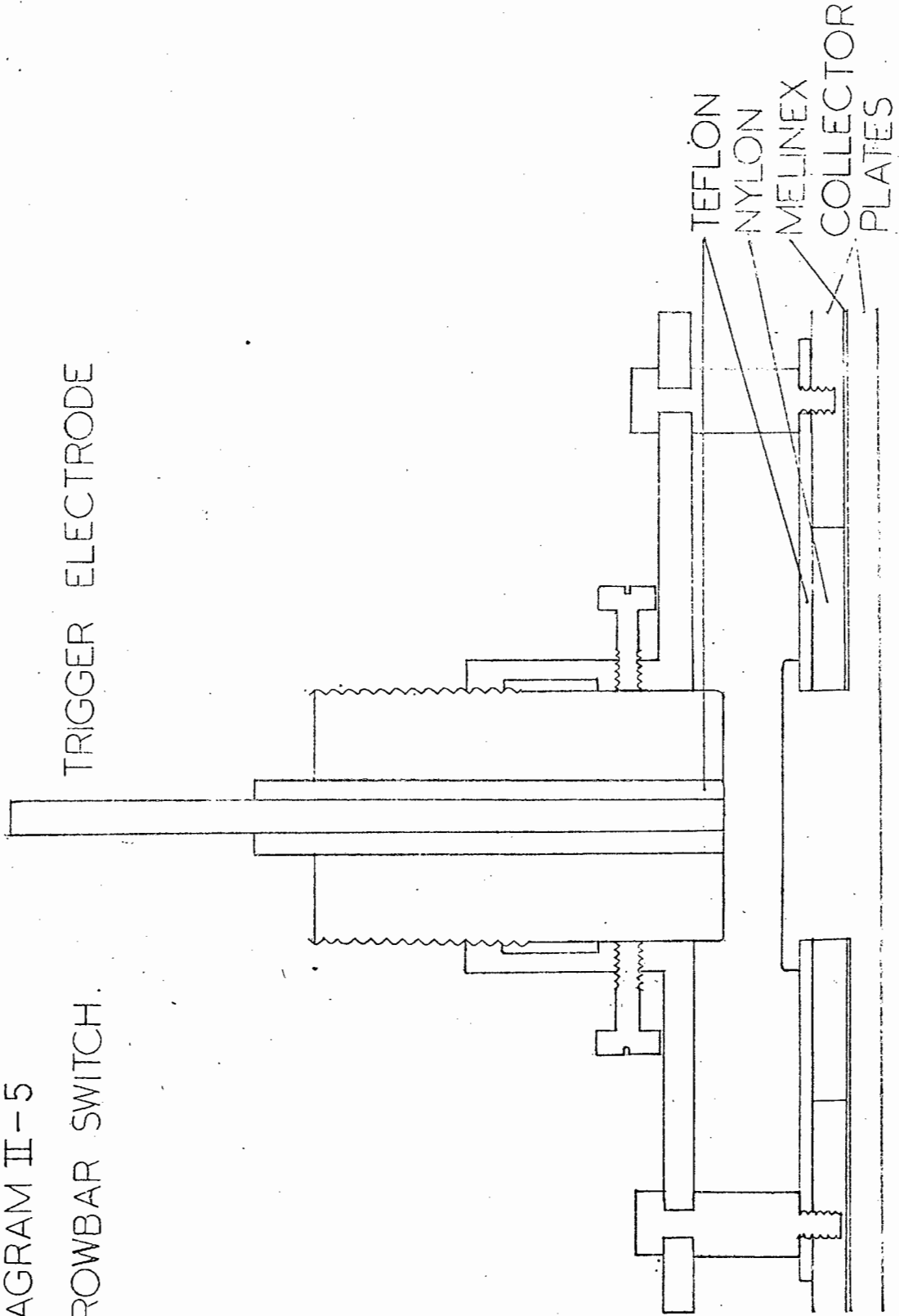
$$\sim 3 \mu\text{sec}$$

if the crowbar switch has an induction of 4 nH (co-axial approximation). This is an order of magnitude too small, as can be seen from the current traces in diagram II - 6.

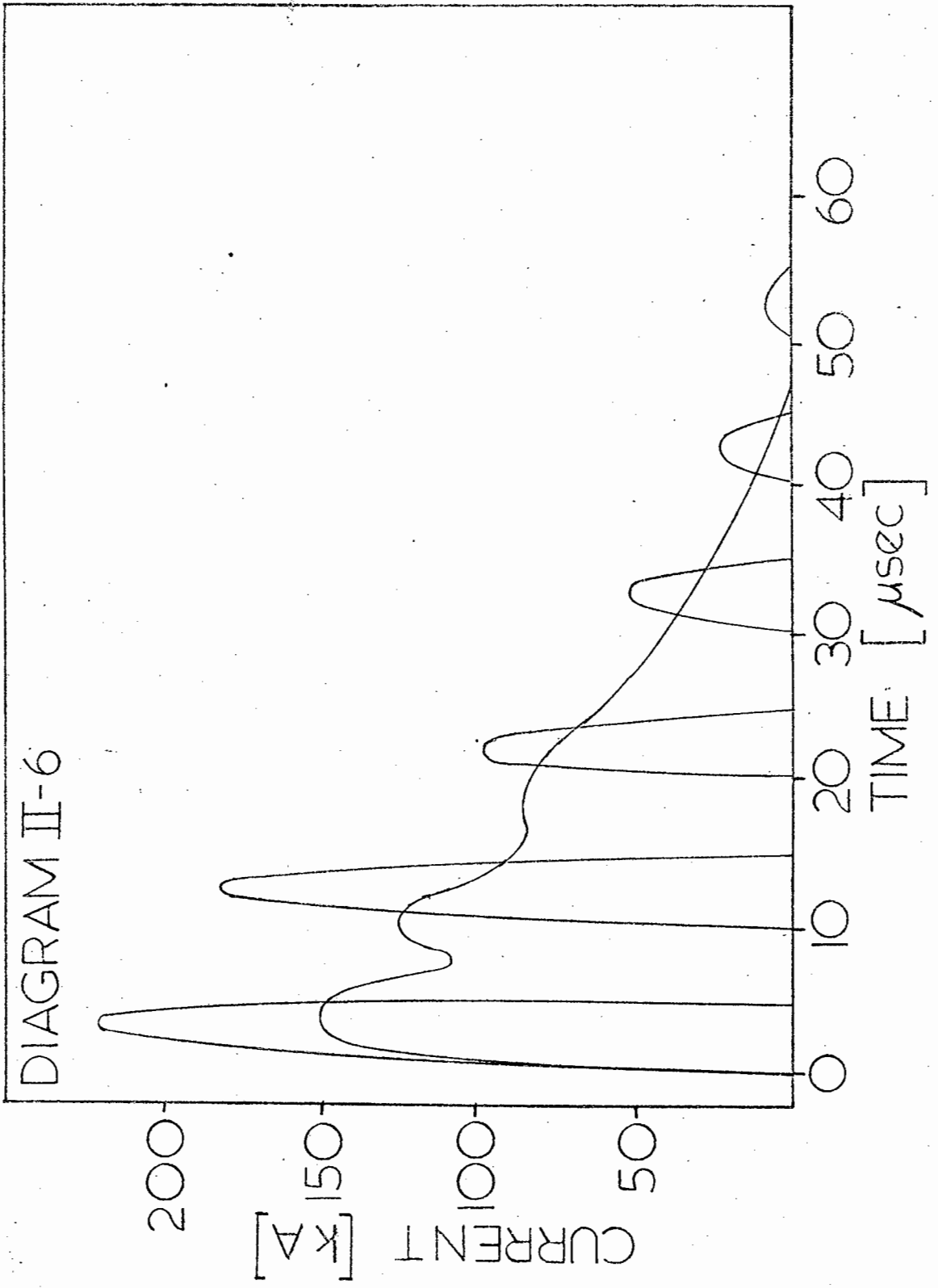
Diagrams II-5/6

DIAGRAM II-5

CROWBAR SWITCH.



SCALE 1:1.3



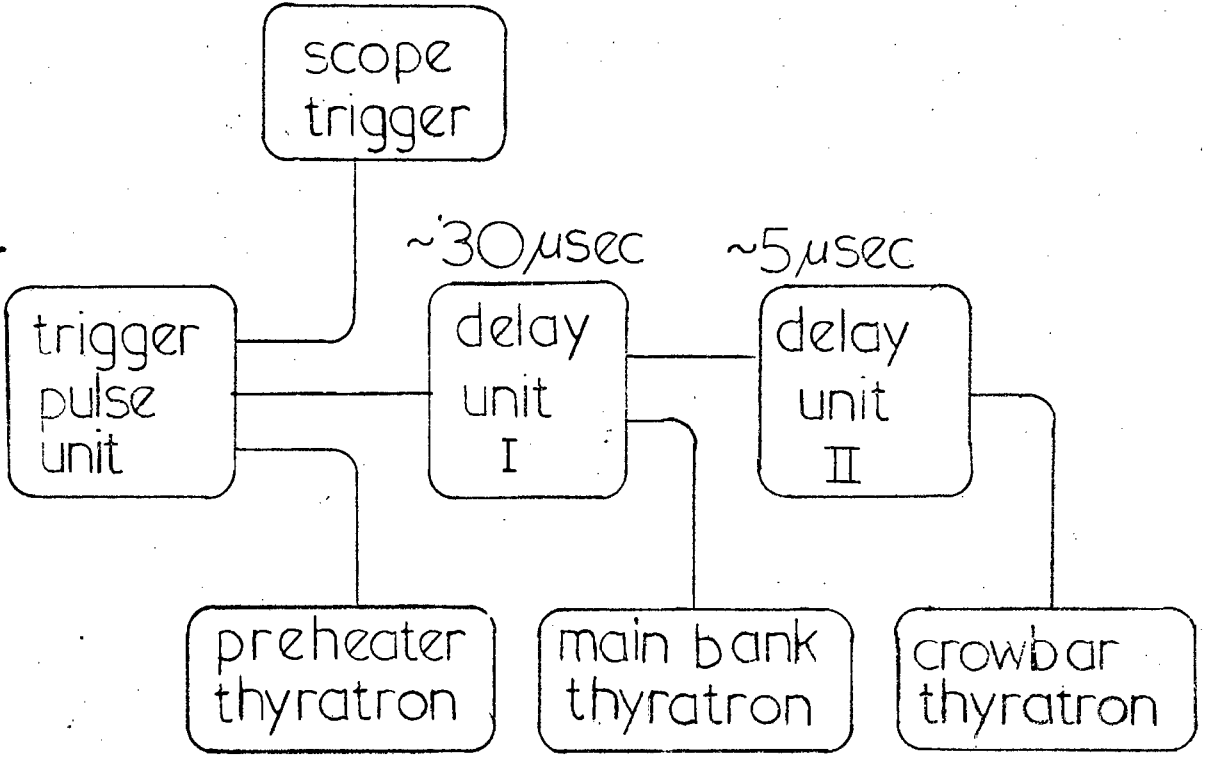
Trigger Units.

The trigatrons for the main bank, preheater bank and crowbar were all triggered by pulses from units similar to that shown in diagram II - 2. The trigger pulses for these secondary trigatrons were supplied by thyatron discharge circuits which were in turn triggered by pulses from another thyatron controlled discharge which fired through a system of delay units, as in diagram II - 7, which shows in block form how all the delays were arranged so as to synchronise the preheater, main bank, crowbar and oscilloscope triggerings.

Diagram II - 7

DIAGRAM II-7

FIRING SEQUENCES



D.C. Magnetic Field.

The D.C. Baseball Seam conductor was wound out of 14 gauge enamelled copper wire to fit the edges of the tetrahedral spire quite closely, it was therefore a "rectangularised" baseball rather than the spherical one described in the literature (see Introduction). The conductor consisted of 35 turns wound closely, making a core of about 2 cm thickness, surrounded by a flexible water-jacket to provide cooling. This jacket was made from a spiral of soft iron wire which was taped with linen cloth tape soaked in a latex solution, then covered with rubber strips glued down and finally a layer of adhesive P.V.C. tape.

The coil had an inductance of 30 mH and a resistance of 3Ω , and was fed by two 75 volt D.C. generators in series, giving a peak current of about 140 amps.

2. VACUUM SYSTEM.

The vacuum chamber was constructed from $\frac{1}{4}$ " plate glass sheets cemented at the edges with Pratley epoxy paste. These joints were only moderately successful and had to be vacuum sealed with shellac. The end plates, one of which had to be drilled for a pumping port, were $\frac{1}{2}$ " glass plates, also fixed in place with epoxy and vacuum

sealed with shellac.

This chamber was very successful, withstanding the shocks of 800 discharges without developing any serious leaks. The brass "O"-ring plate was cemented into the port, again with epoxy.

The vacuum system consisted of an oil diffusion pump, backed by a rotary pump. The pressure was measured by a pirani gauge (calibrated against a McLeod gauge) in the higher ranges (10μ and upwards), and an ionization gauge in the lower ranges.

3. OPTICAL SYSTEM.

A row of $1/8$ " holes was drilled in the wall of the spire, perpendicular to the axis, and in the mid-plane of the spire. The light leaving the plasma through these holes was focussed onto the entrance slit of a Heath EM-700E scanning monochromator. The detector used was an EMI-6255-B photomultiplier tube.

The signals were recorded on a Tektronix 551 double beam oscilloscope and photographed. Scope II was a storage screen oscilloscope used to monitor each discharge.

CHAPTER III

FIELDS

CHAPTER III

The A.C. magnetic field of a spire identical to the one used in these experiments has been measured and empirical formulae generated to fit the field (reference III-1). This analysis showed a magnetic well with a depth of 6% in the mid-plane and in the axial-planes, but serious "leaks" appeared in the off-axis planes. Attempts at a numerical calculation of the D.C. field were made, but showed no well for a purely azimuthal current. Calculation of the A.C. field would have required knowledge of the inductance of the different azimuthal paths round the well. This was virtually impossible to find, so the calculation was not attempted.

The measured field value at the centre of the coil was 1.2 webers/meter², this agrees with an approximate calculation based on energy density considerations.

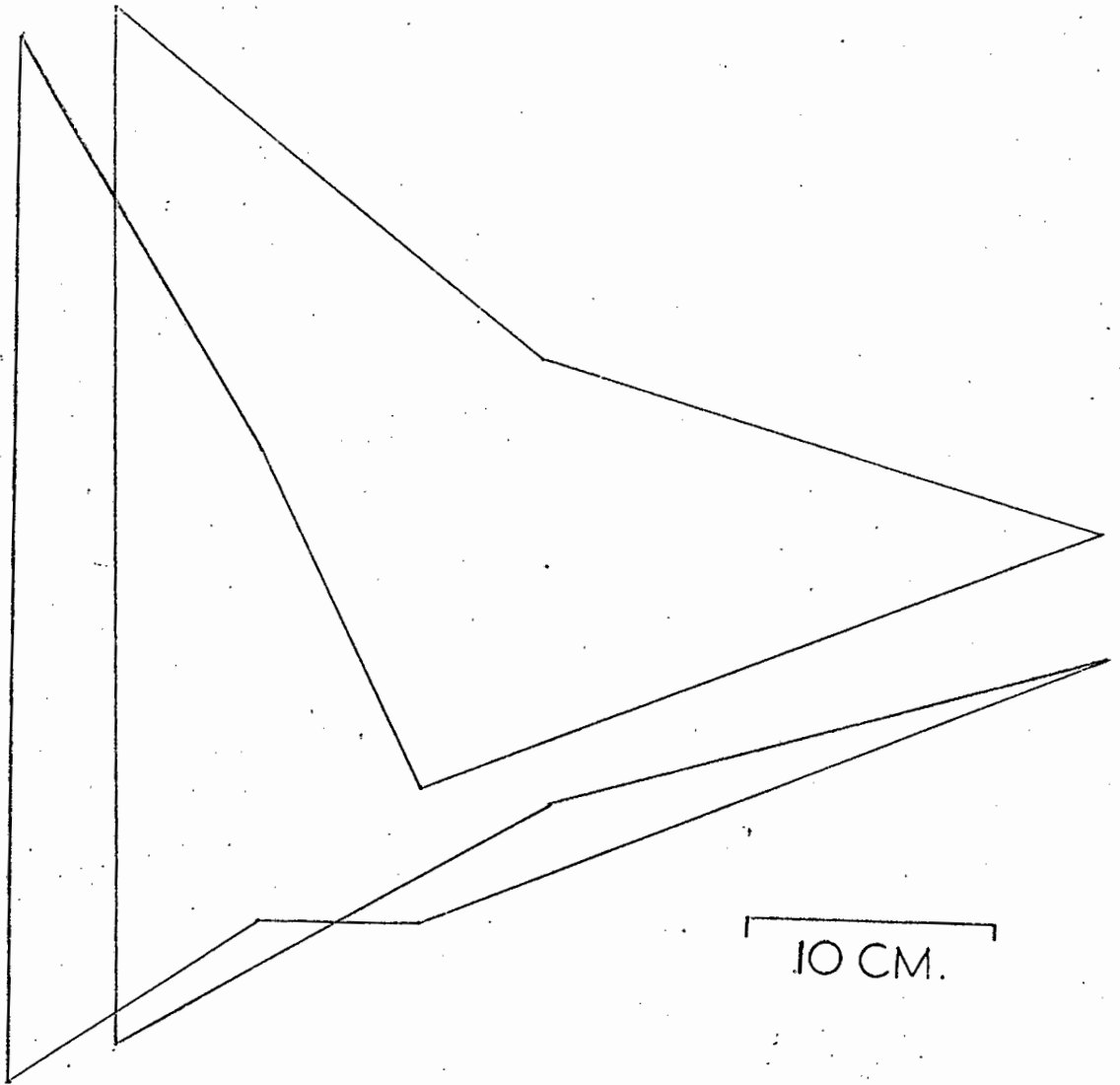
In order to cure the "leaks" in the spire field, an external D.C. field was added. This field was produced by a modified baseball seam conductor, made to fit the edges of the spire.

Attempts to calculate the field of this conductor produced analytic results involving four terms for each linear element of the conductor. Though the answer was analytic, the general shape of the field was far from obvious. A numerical computation of this field would have been possible, but the only point of real interest as far as the experiment was concerned, was the peak value of the field inside the spire. This value was quite easily calculated from the expressions obtained for the exact field values.

The maximum D.C. current available was 140 amps. The calculation showed 35 turns of the conductor shown in diagram III-1 to be necessary to produce a peak field of 0.12 webers/meter² near the conductors (4 cm from the outside), and a mid-point field of 0.04 webers/meter². The peak value is only 10% of the spire field value, but the "leaks" are 6% of the average field value, so the D.C. field should be high enough to plug these leaks.

DIAGRAM II-1

IDEALISED BASEBALL SEAM



CHAPTER IV

EXPERIMENTS

CHAPTER IV

1. AIMS

The experiments conducted with the apparatus described were all spectroscopic determinations of the behaviour of the Electron temperature T_e , and the Electron density N_e of Hydrogen plasmas in the magnetic well. It was hoped that some indication of the containment properties of the fields described in Chapter III could be inferred from the observed time-variations of the temperature and density (mainly the latter) of the plasmas trapped in the well.

Similar temperature and density measurements were made on a θ -pinch apparatus (length 32 cm, diameter 10 cm). These results were used for comparison with those obtained from the magnetic well. Both field configurations had radial compression, the θ -pinch had open ends and the well had partly closed ends. A comparison of the decay rates of electron densities should show just how big the end losses in the well are.

Temperature measurements were made viewing along the axis of the well, and also in the mid-plane. The difference in these temperatures should be some indication of how much cold plasma is spread out along the axis and

not compressed into the centre of the vacuum chamber.

2. THEORY EMPLOYED

The density determinations were made by measuring the width of H_{β} and using the formula given by Griem (reference IV-1)

$$N_e = C(N_e, T_e) \Delta\lambda^{3/2}.$$

The coefficient $C(N_e, T_e)$ is tabulated by Griem (reference IV-2) for H_{β} in the temperature range

$$5,000 - 40,000^{\circ}\text{K}$$

and in the density range

$$10^{14} - 10^{17} \text{ cm}^{-3}.$$

The plasmas obtained fitted into these ranges.

The temperature was calculated from the observed intensity ratios of the Helium lines He_{II} (4686 Å) and He_{I} (5875 Å). The Helium being introduced as a 5 - 10% impurity in Hydrogen. The calculation was done using a formula from Griem (tabulated in reference IV-3) which is dependent on LTE conditions prevailing, and a density of less than 10^{18} cm^{-3} . This last condition was satisfied but the plasma falls between the LTE and semi-corona domains. For this reason the temperatures given must not be considered absolutely correct, but only an indication of the state of the plasma. In the experiments, the real interest was not in the absolute temperatures, but rather

in the rates of change, which are adequately given by the curves in Chapter V.

3. TECHNIQUES

In all the experiments a radio-frequency pre-ionization current was fed into the gas via two electrodes fastened onto the end of the vacuum chamber. The R-F generator produced 500 watts at 30 MHz.

The preheater and main-bank current was recorded along with the photo-multiplier signal on the twin-beam oscilloscope. This current trace was used to provide a time-zero for the light output trace, and also to monitor the operation of the crowbar.

The oscilloscope traces were photographed on 35 mm film. The negatives were projected (with a photographic enlarger) onto graph paper and the traces drawn onto the paper with a suitable magnification, thus providing a readily useable, time-resolved picture of the light output from the plasma.

The current signal came from a probe (30 turns, 0.75 cm^2) placed near the open end of the spire. The signal was integrated by a R-C circuit having a time constant of $100 \mu\text{sec}$.

In the density measurements, the vacuum chamber

was pumped to a base pressure of 10^{-4} mm Hg, then filled with Hydrogen to about 100 microns, pumped to about 10^{-3} mm Hg and then filled accurately to the final pressure of 100 microns. This flushing procedure improved the reproducibility of the discharges a lot and was carried out before every discharge.

The line width was measured by recording the light output in 0.2 \AA bands around the line centre. Generally 10, 1 \AA steps were enough to cover H_{β} . The line shape at any time could then be obtained by plotting the amplitude of the photomultiplier signal against the wavelength. The reliability of this method depends very much on the reproducibility of the discharge. Fortunately any large irregularity was blatantly obvious in the line shape as the intensity at one wavelength was consistently high or low. The reproducibility of the discharges was generally very good, but the first 5 micro-seconds of all the discharges tended to be a bit chaotic, giving unreliable line shapes.

For the temperature measurements, the exit slit was opened wide, ($\sim 0.2 \text{ mm}$, 4 \AA) and the monochromator set on the wavelength of the line being observed. The total intensity in this wavelength band was recorded in the same way as the intensities were recorded for the density

measurements, excepting the final filling where the chamber was filled up to 100 microns with Helium. The filling was done with needle valves, operating at a back pressure of 10 lbs/sq in. This filling was not very accurate, the smallest controllable pressure change being 2 microns.

The photomultiplier tube was calibrated for wavelength sensitivity by scanning the spectrum emitted by a Tungsten filament. By assuming the filament to be a black body radiator, a calibration factor for the intensity ratio of the two Helium lines could be calculated.

The temperature of the filament was found from the relative resistance (R_T/R_{273}). (Reference IV-4).

The Tungsten filament spectrum is shown in diagram IV-1.

$$\text{Resistance Ratio } R_T/R_{273} = 8.605$$

This gives a temperature of 1630°K

The ratio of amplitudes at two wavelengths λ_1 and λ_2 is

$$I_1/I_2 = \left(\frac{\lambda_2}{\lambda_1}\right)^5 \left(\frac{e^{\alpha/\lambda_2}-1}{e^{\alpha/\lambda_1}-1}\right)$$

$$\text{where } \alpha = \frac{hc}{kT} = 8.83 \times 10^{-6} \text{ metres}$$

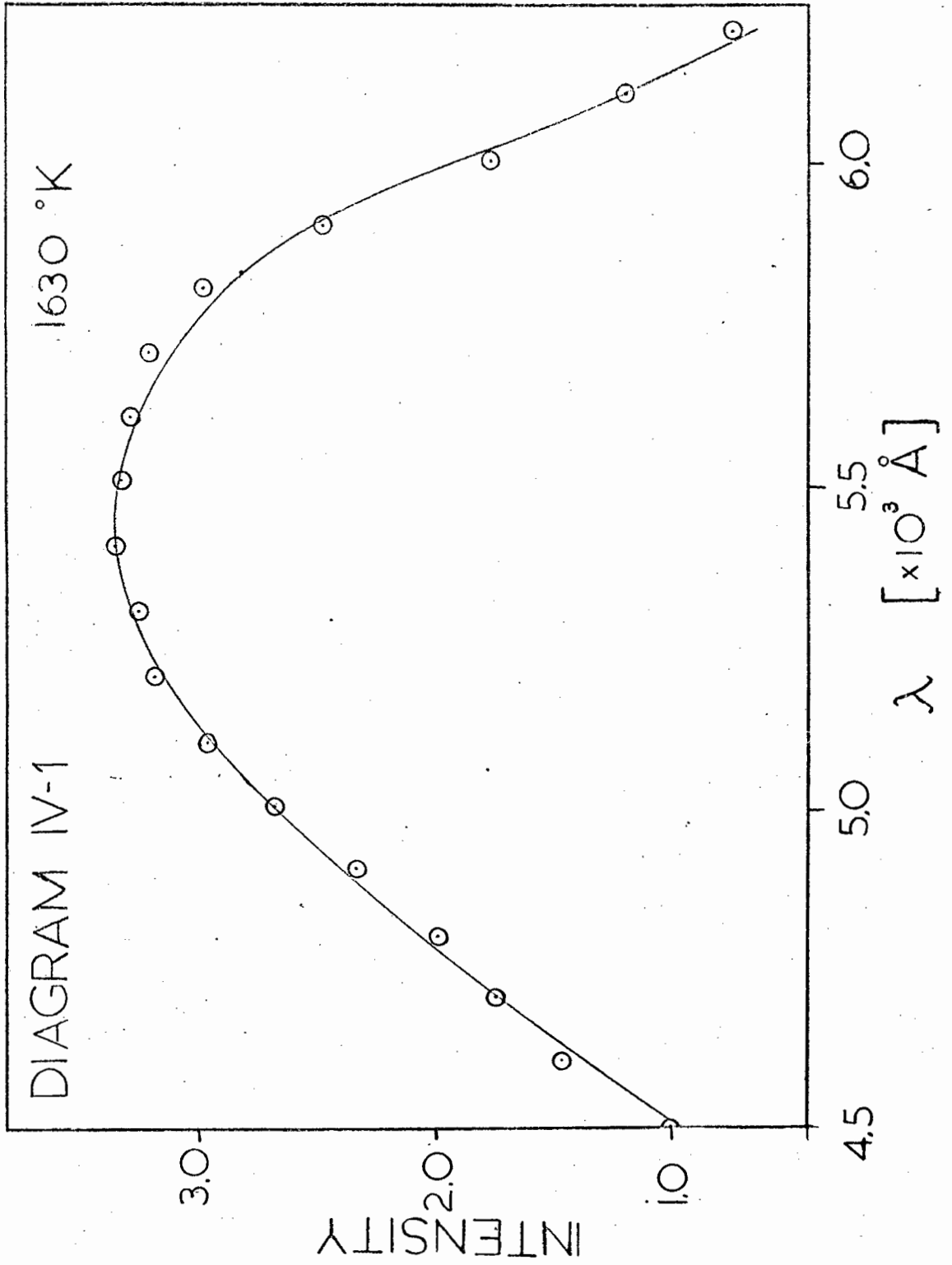
$$\lambda_1 = 4686 \text{ \AA}, \quad \lambda_2 = 5875 \text{ \AA}$$

The calculated ratio is thus 7.005×10^{-2} .

From diagram IV-1, the observed ratio is

0.6250,

giving a correction factor of 0.112. This correction will be applied to all measured intensity ratios of the two Helium lines.



CHAPTER V

RESULTS

CHAPTER V

1. DENSITY MEASUREMENTS

Results are shown of density measurements made on the tetrahedral spire, with and without the external D.C. field. The measurements were all made viewing in the mid-plane of the spire.

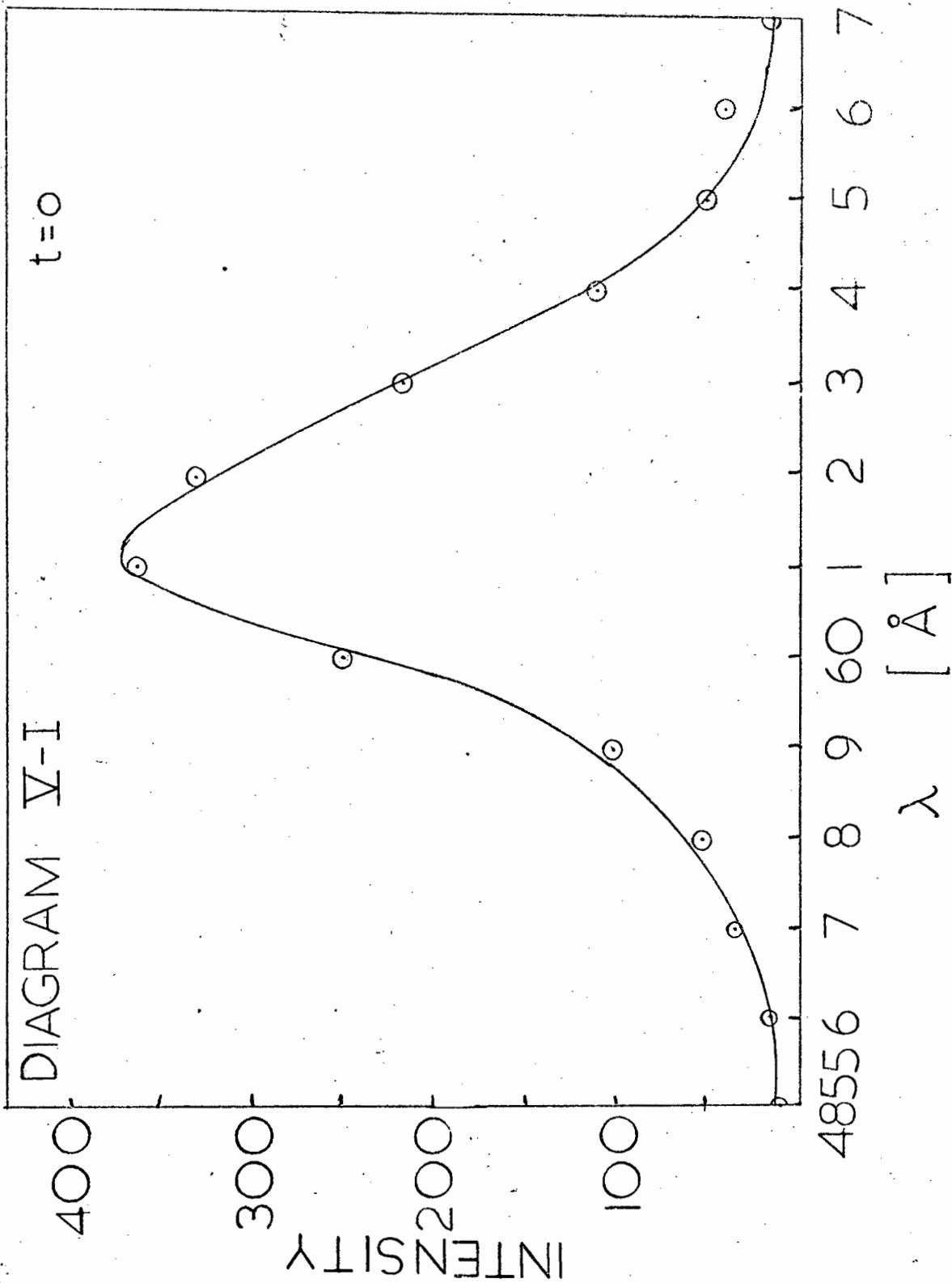
The oscilloscope traces of the light output are not shown, but three typical H_{β} line profiles are shown, indicating the reproducibility (by the smoothness of the profiles) and the main features of the line profile as viewed at different times.

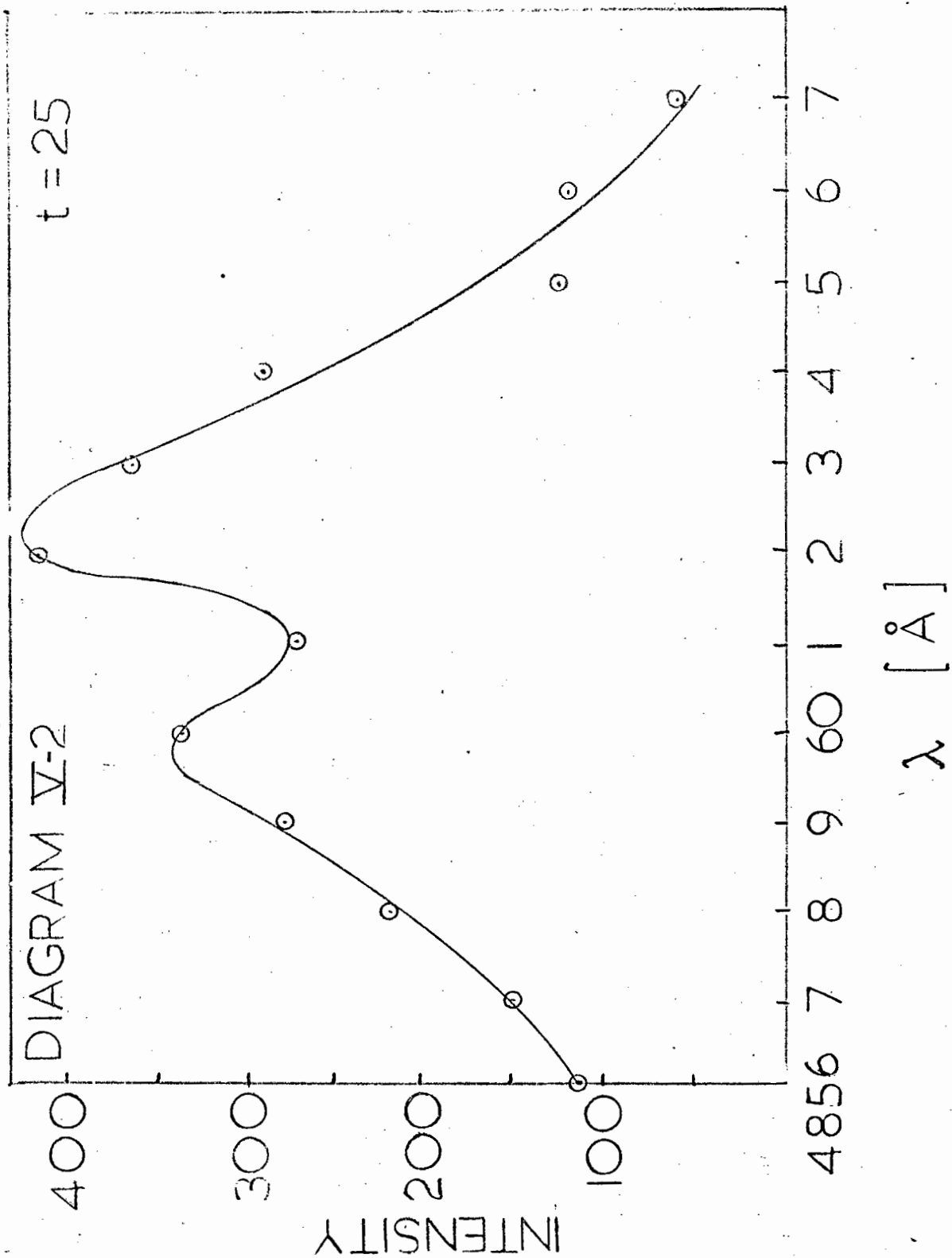
The first line profile shown was measured as the main bank fired, it gives the initial density of the plasma. The second line profile was measured 20 microseconds after the main-bank fired, and shows the characteristic asymmetric dip near the peak of the line, this due to self absorption by the colder plasma. At this time, the peak shows a red shift of about 1 \AA .

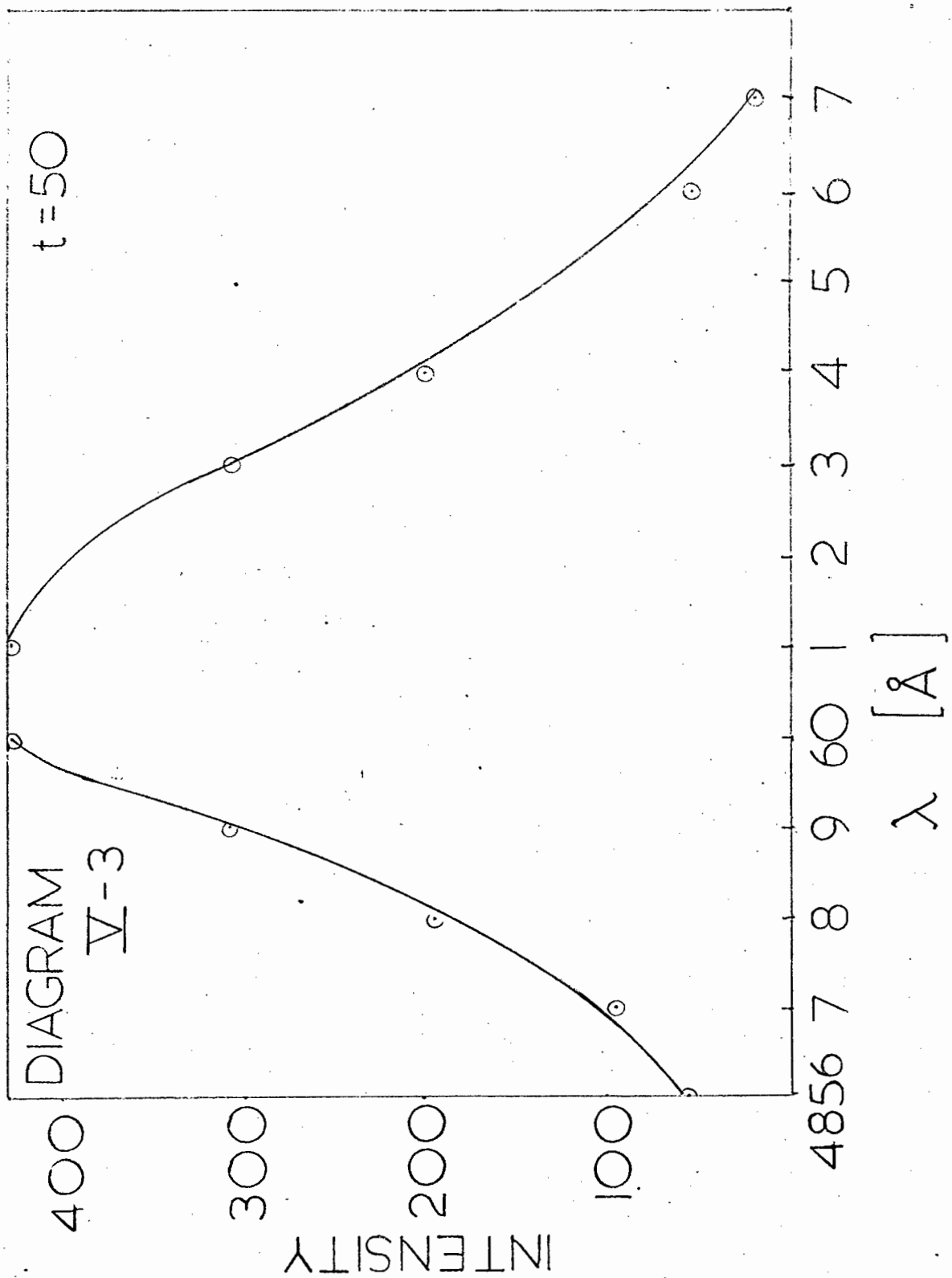
The third profile shown was measured at 50 microseconds after the main bank fired, it shows no self-absorption and no red shift, but still a considerable half-width (FWHM). Figure V-5 shows the time-resolved electron

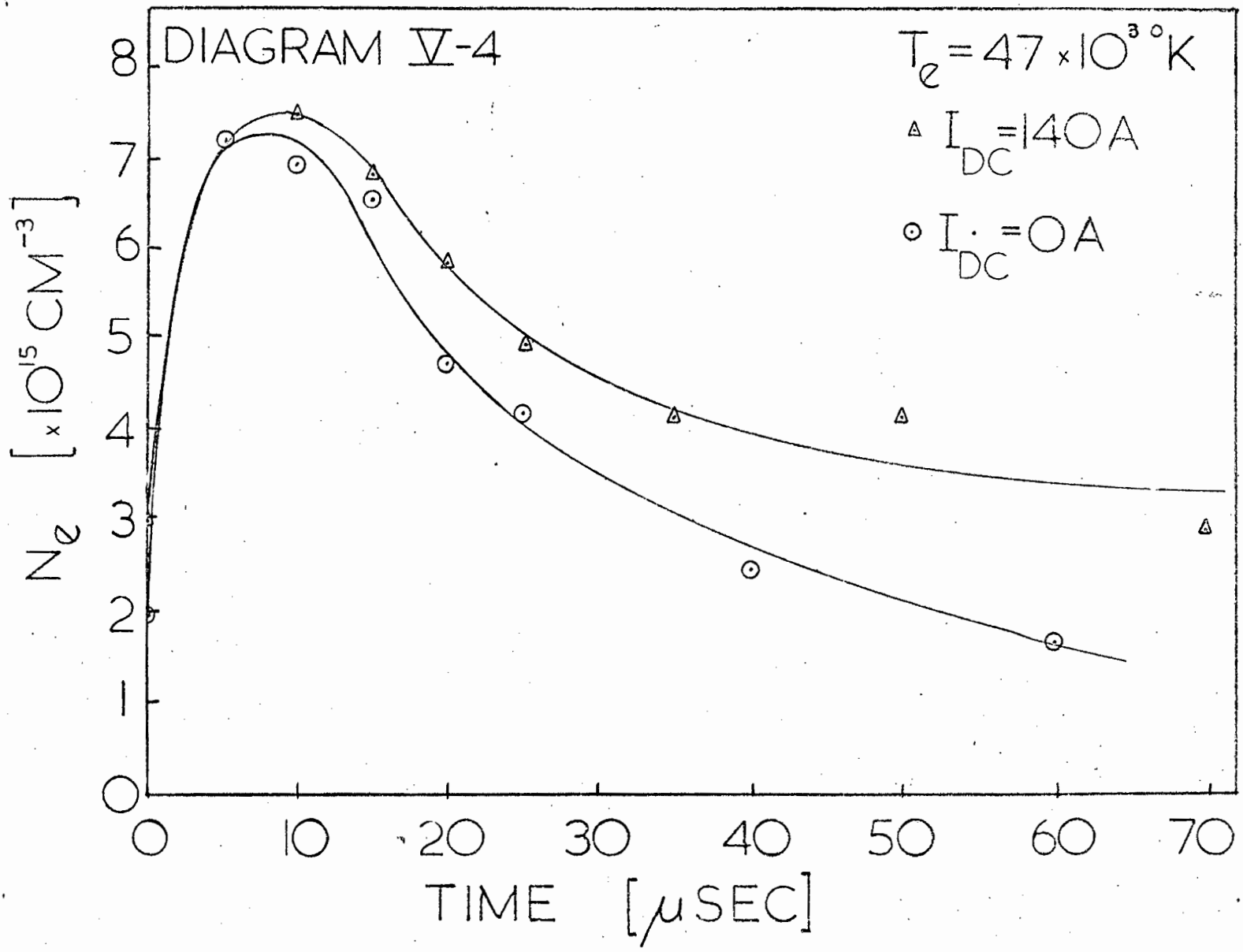
density in the θ -pinch. All the density calculations were performed using a temperature of 47×10^3 °K.

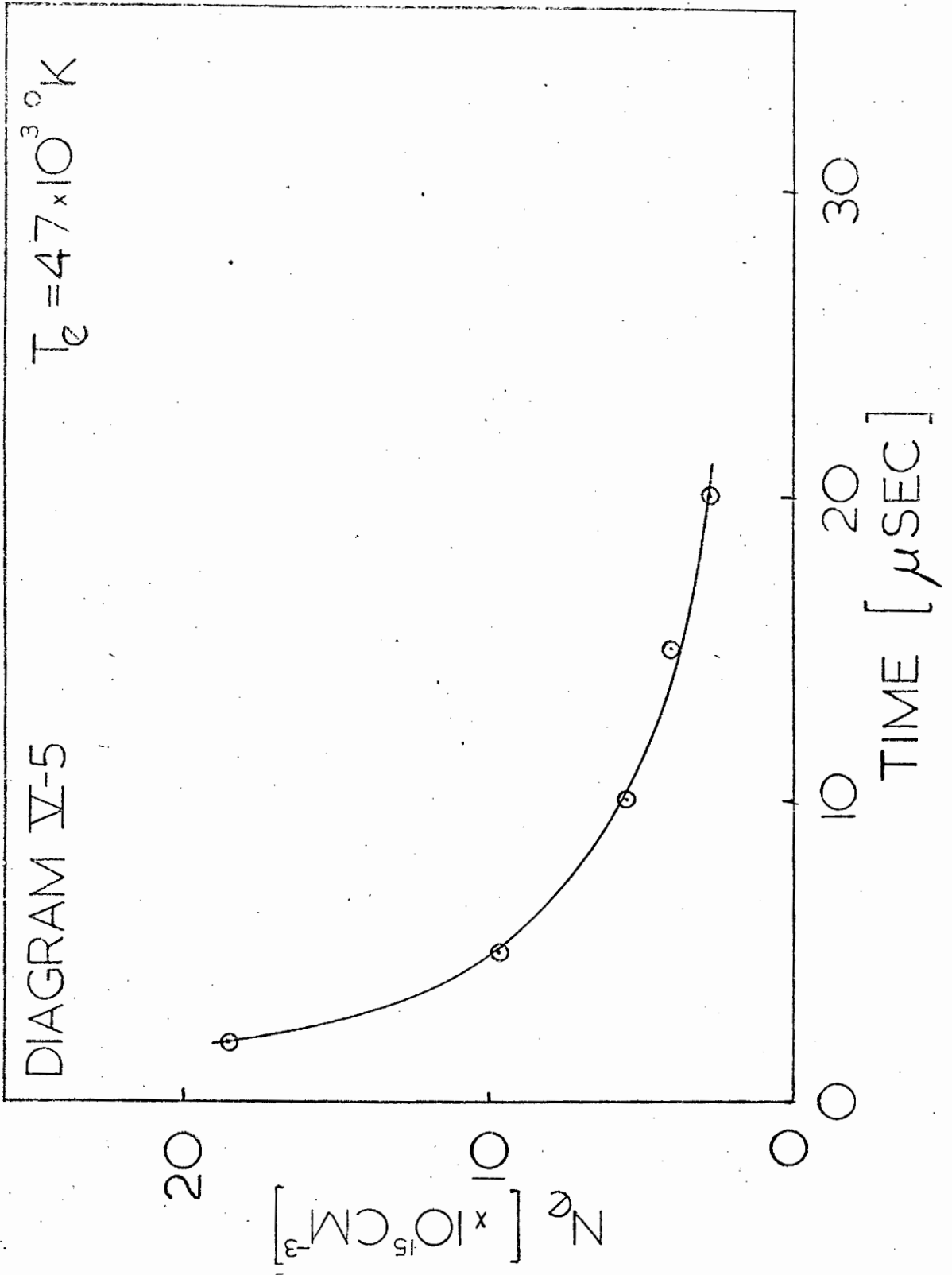
Diagram V-1 /











2. TEMPERATURE MEASUREMENTS

Results are shown of temperature measurements made on the tetrahedral spire, with and without the external D.C. field, viewing in the mid-plane, and along the axis of the spire.

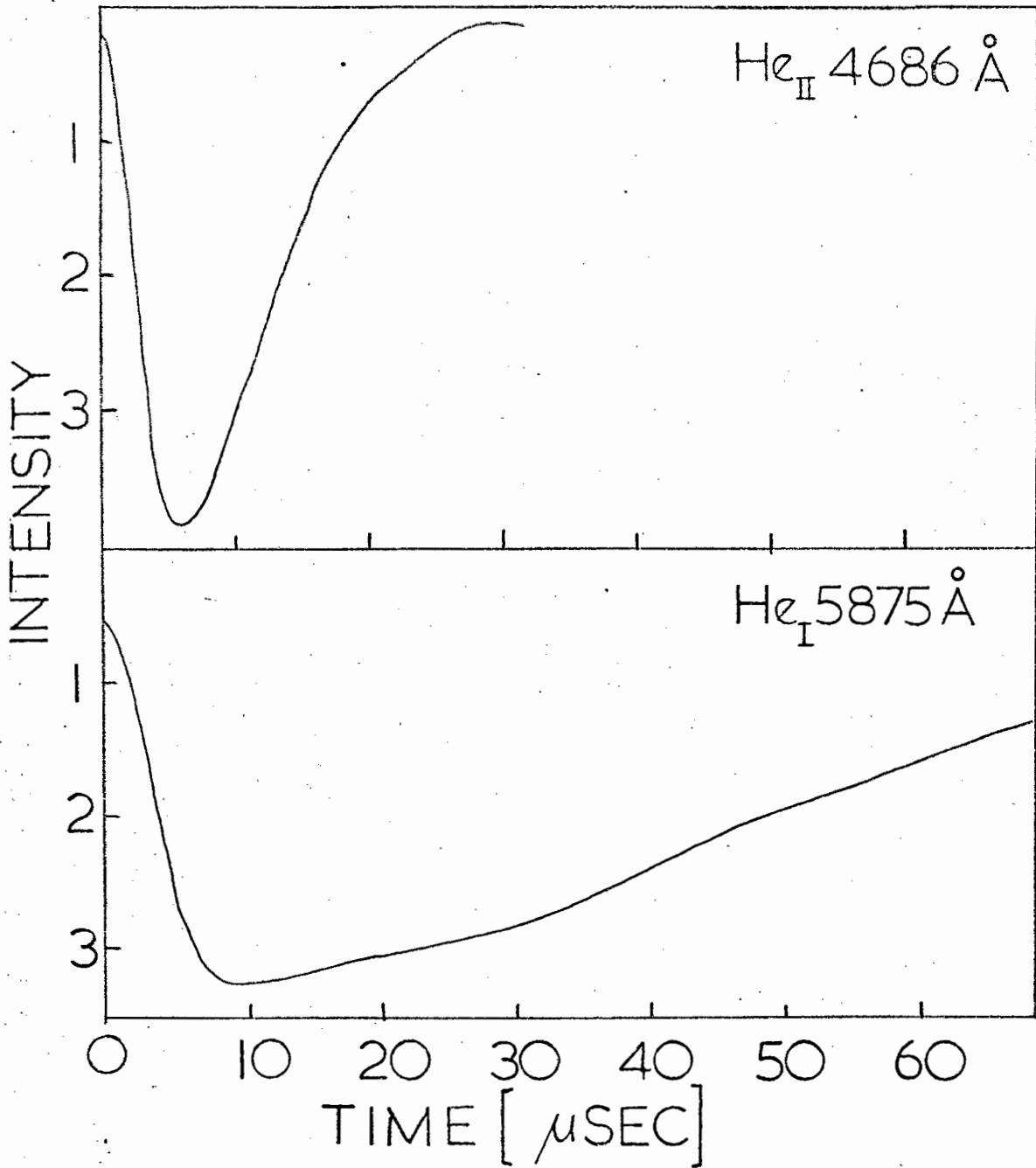
The intensity curves of the Helium lines are all averages of 3 oscilloscope traces, the variation between traces being less than 5%.

Diagrams V-8 and V-11 show the decay of the electron temperature. Where no value is given for $t = 0$, the line ratio was so small as to be outside the range of applicability of the theory.

Any attempt to evaluate the accuracy of the temperature and density curves would be no more than guesswork. The density curves can be trusted up to about 5%, but the temperatures could be up to 20% out. The main sources of error being in the theory used to calculate the plasma parameters from the measured quantities.

AXIAL VIEWING DIAGRAM ∇ - 6

$$I_{DC} = 0 \text{ A}$$



AXIAL VIEWING DIAGRAM V 7

$I_{DC} = 140 \text{ A}$

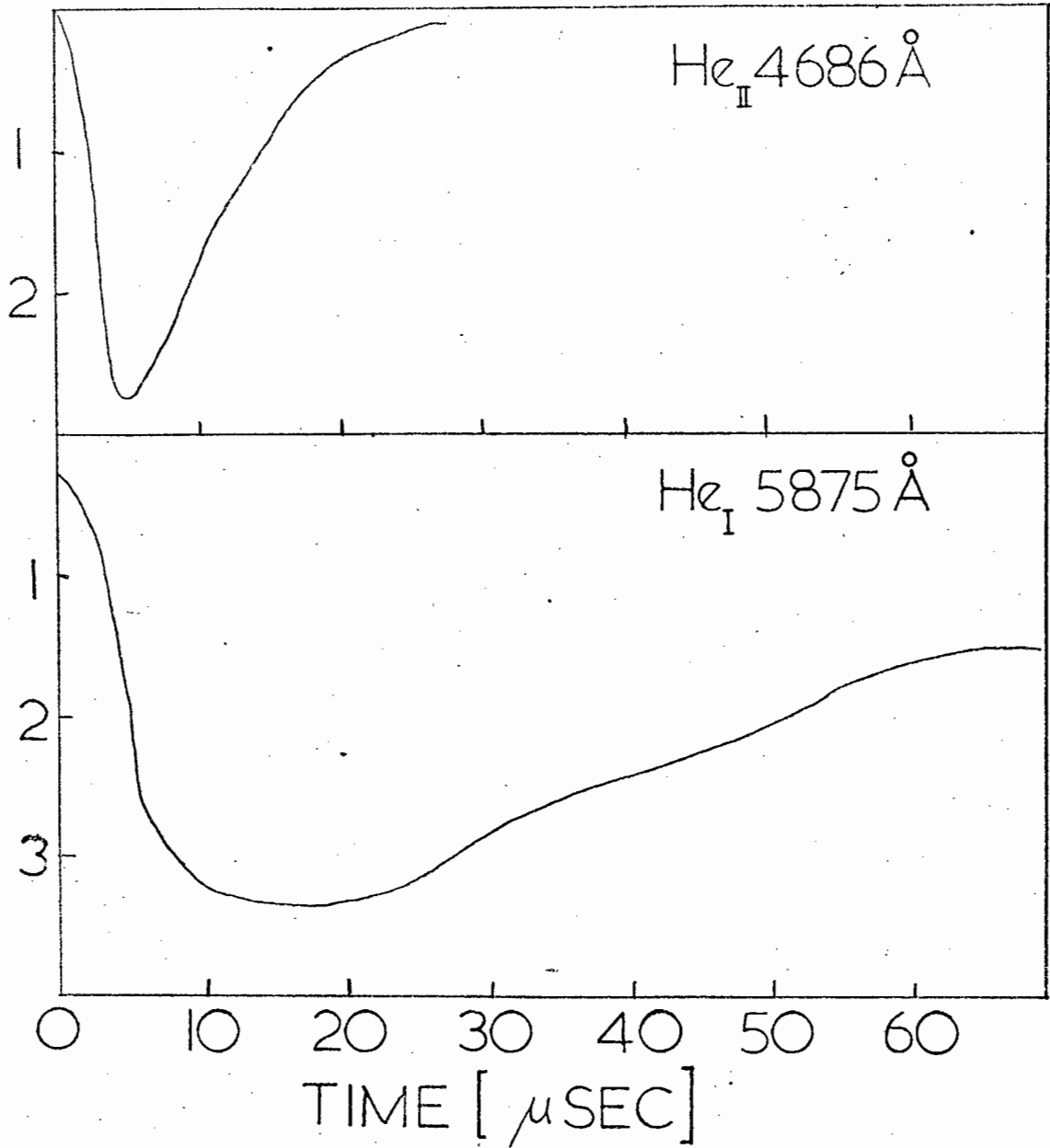
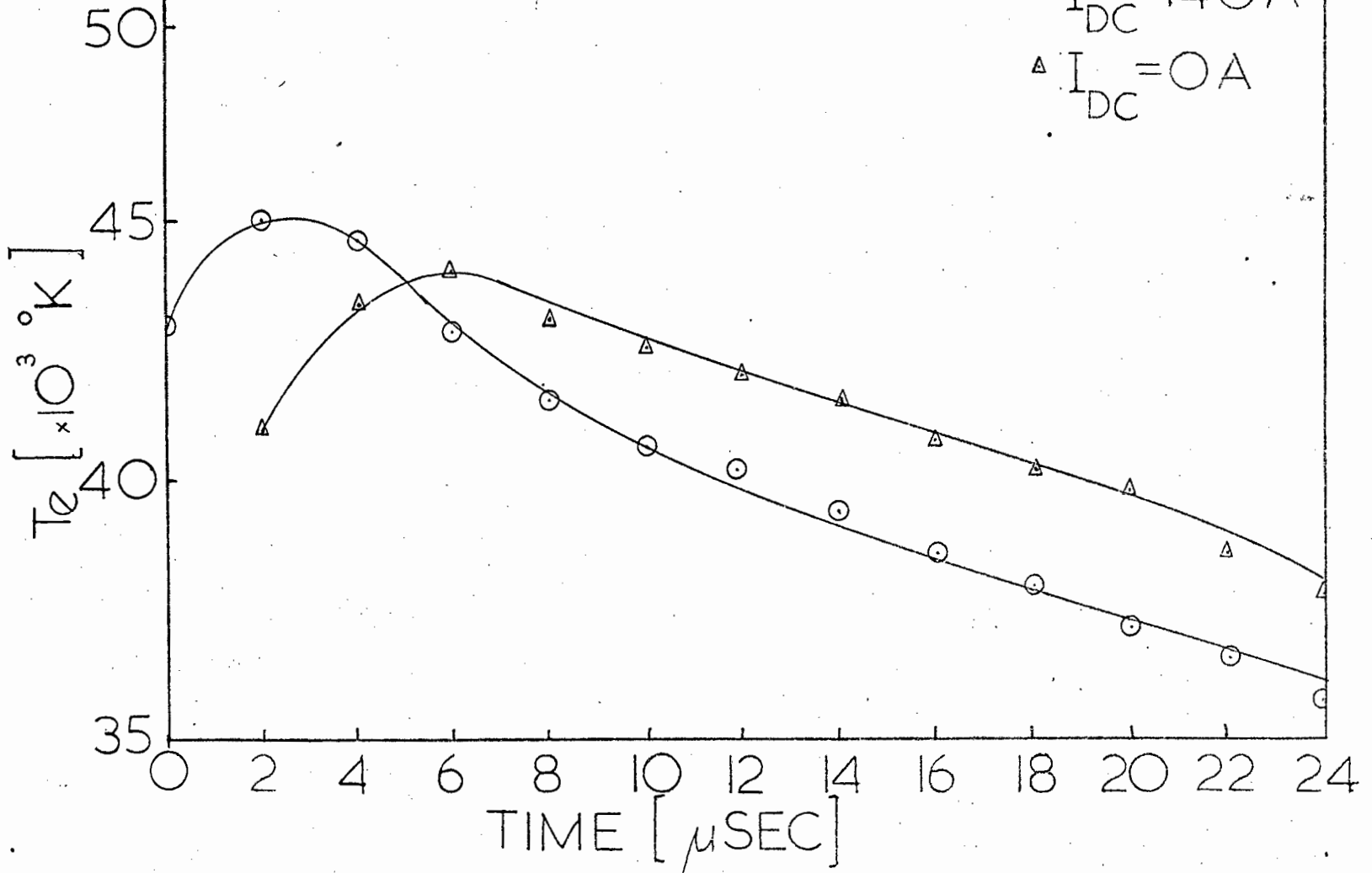


DIAGRAM V-8

AXIAL VIEWING

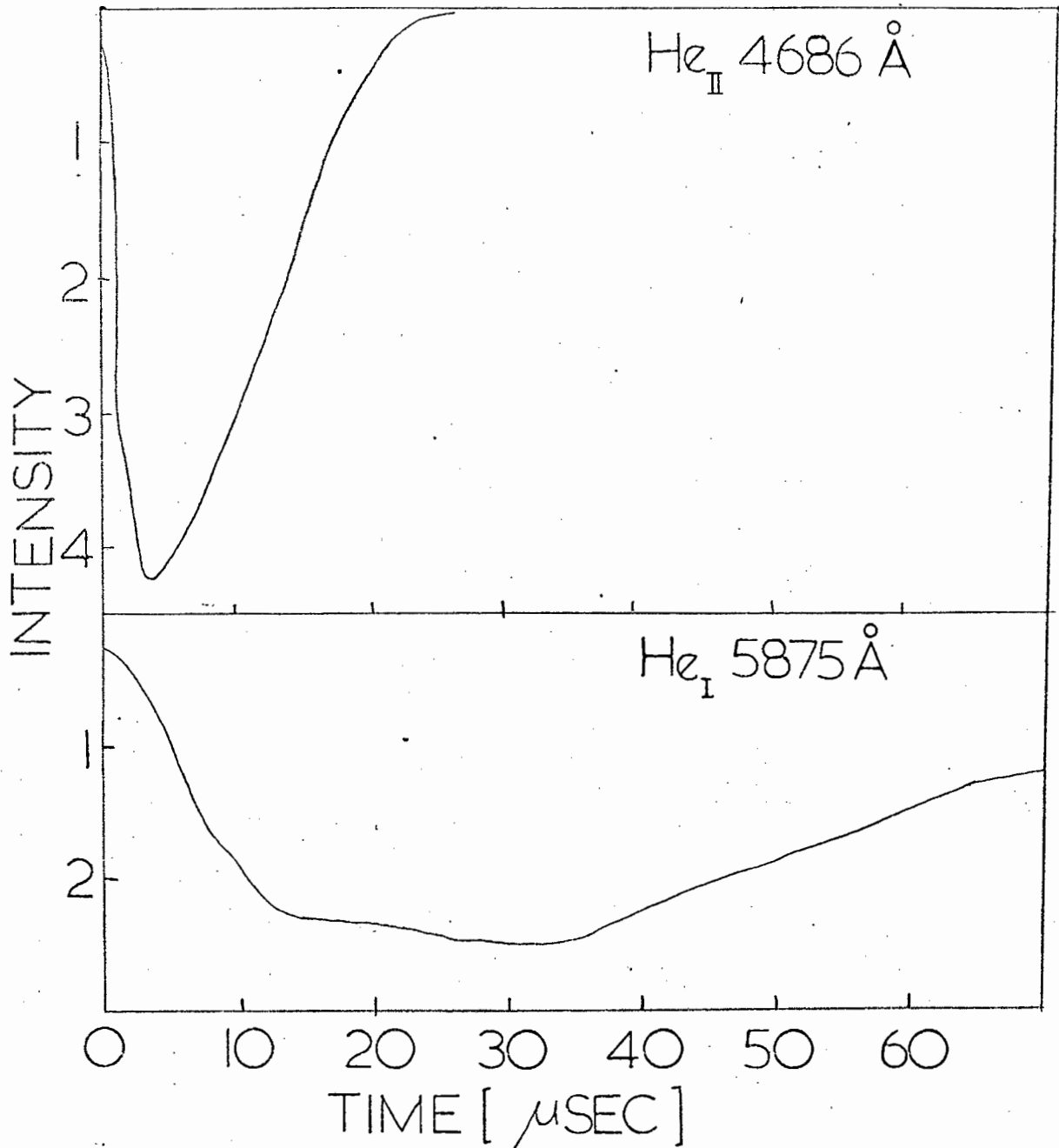
○ $I_{DC} = 140A$

△ $I_{DC} = 0A$



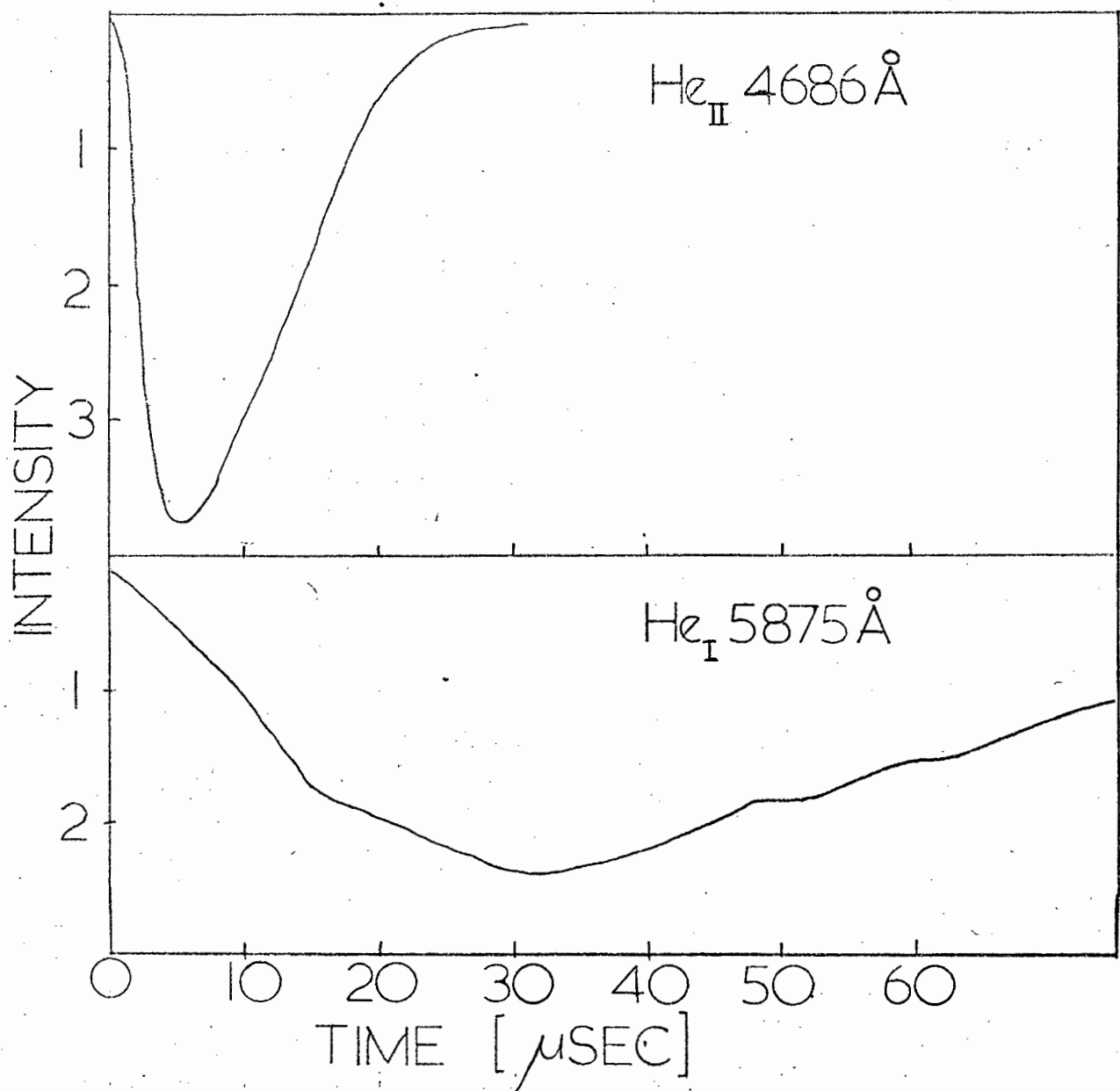
MID-PLANE VIEWING DIAGRAM V-9

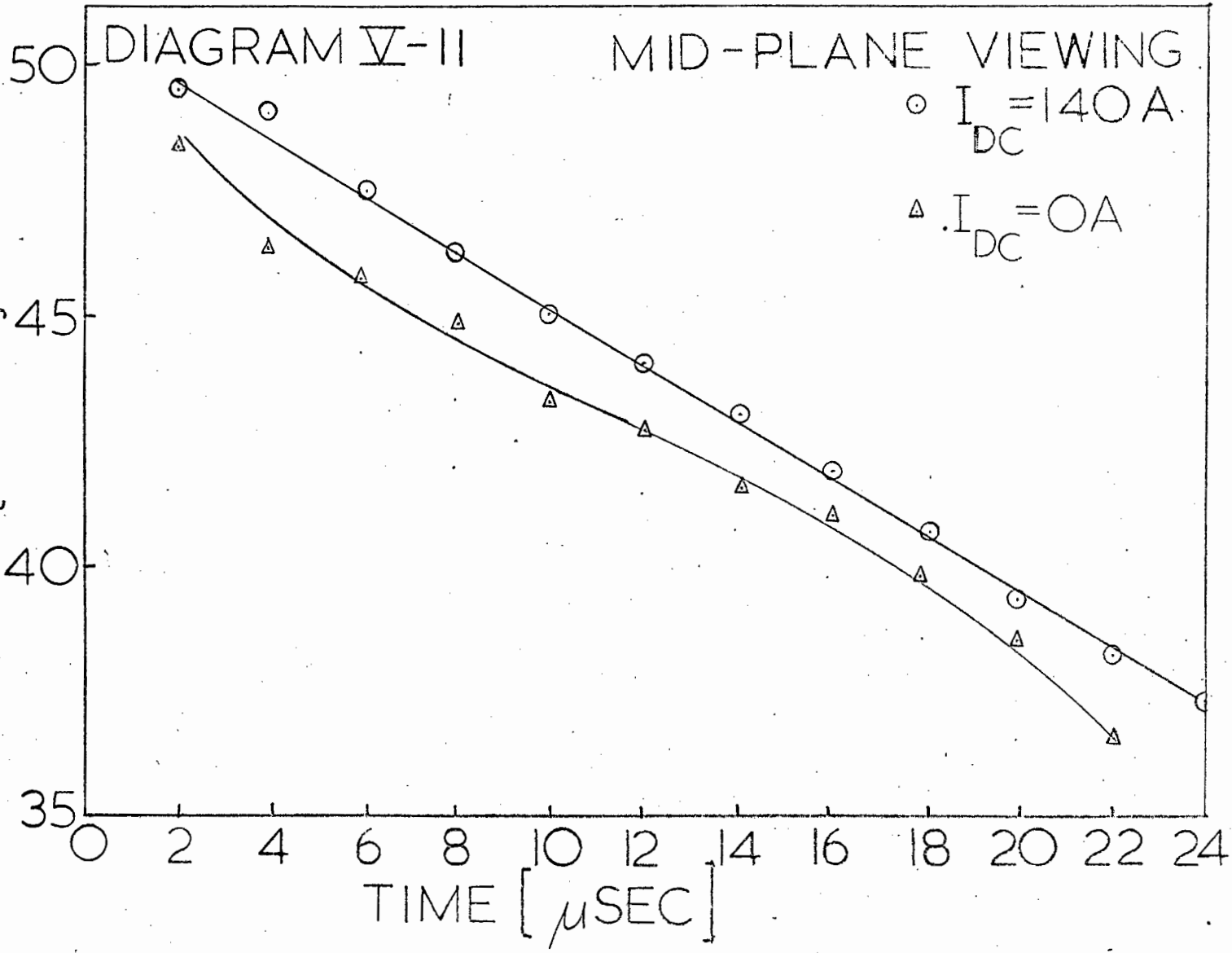
$I_{DC} = 0A$



MID-PLANE VIEWING DIAGRAM V-10

$I_{DC} = 140A$





CHAPTER VI

CONCLUSIONS

CHAPTER VI

From diagram V-4, the electron density can be seen to rise rapidly from an initial value of about $2.5 \times 10^{15} \text{ cm}^{-3}$ to about $7.5 \times 10^{15} \text{ cm}^{-3}$ in 9 microseconds, whether or not the external D.C. field is present. The current rise lasts for only 4 microseconds (diagram II-6). This difference in times is due to the axial compression in the spire being much slower than the azimuthal one.

After the initial compression, the presence of the D.C. field makes an obvious but not startling difference to the decay of the electron density, which has essentially the same shape in both cases without the external D.C. field, the electron density returns to the initial value after 45 microseconds, while the presence of the D.C. field increases this to 70 microseconds.

A comparison of diagrams V-5 and V-6 shows that the theta-pinch apparatus produced much higher peak densities, but a very fast decay. The curve is very closely exponential, having a decay time of 4.2 microseconds. The density curve for the spire field alone has an approximately exponential decay with a decay time of 21

microseconds. For the spire field with the external D.C. field, the decay is not even approximately exponential, so a decay time would be meaningless.

A comparison of figures V-8 and V-11 show the temperatures observed along the axis to have lower values at all times, and a slower rise than those observed in the mid-plane. This indicates a lot of cold plasma along the axis of the spire, and a reasonably sharp edge to the plasma in the mid-plane.

In both cases the presence of the external D.C. field makes little difference to either the value or decay of the temperature. This leads to the conclusion that the predominant mechanism for temperature decrease is energy loss by radiation, rather than expansion. This conclusion is supported by the fact that the temperature drops in about 20 microseconds while the density has dropped to only half its peak value after this time.

In conclusion it can be said that the addition of the external D.C. field did increase the containment times of plasmas inside the spire field. The diagnostics used were capable of giving little more information about the plasma except to show that there is a large mass of cold plasma lying along the axis of the spire.

A more detailed study of the plasma dynamics is indicated. A simple extension of the present method would be to view diagonally, i.e. along one of the off-axis planes through the centre of the plasma. This should provide enough data for a mathematical inversion process leading to density - and possibly also temperature contours inside the spire at different times.

As a plasma containment device, the tetrahedral spire with its field modified as has been described does not produce particularly exciting results, though a more careful analysis might show better ways of improving the spire's containment properties.

ACKNOWLEDGEMENTS

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