AN EXPERIMENTAL INVESTIGATION OF
THE STARK BROADENED PROFILES
OF He II 3203 AND He II 4686
by
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ABSTRACT

Experimental profiles of the He II lines at 3203 Å and 4686 Å have been obtained from a well diagnosed helium plasma. The plasma was produced in a low power z-pinch discharge contained in a vessel of 15 cm diameter and 60 cm length. Uniform plasma columns were located and studied by means of two moveable quartz limiter tubes. The effect of the tubes on the measured electron temperature and density due to cooling and evaporated impurities was measured and the tubes were positioned so as to select a uniform plasma column for study. Electron temperatures were determined from the intensity ratio of the lines He II 4686 and He I 5876 using a theory that considered finite escape probabilities for the Lyman α resonance photons. Electron densities were determined from the width of the He I 5876 line. Corrections were applied for ion broadening due to doubly charged ion perturbers. An electron temperature of 4.0±0.4 eV and an electron density of \((6.1±0.6) \times 10^{23} \text{m}^{-3}\) were determined for the axial plasma occurring soon after the pinch phase. The experimental profile of He II 4686 as measured by a spectrometer-optical multichannel analyzer arrangement was compared to theoretical profiles resulting from a treatment of the electron broadening collisions as single event impacts (Kepple (1972)) and from a treatment of the electron broadening which considers the time development in the
collision process (unified classical-path theory) (Greene (1976)). The experimental profile was found to lie midway between the theoretical profiles. Agreement between the experimental and unified classical-path profile in the near line wings was good. Agreement between experimental and electron impact results for He II 3203 was not good with a 60% disagreement in line widths. The He II line had a double peak with the peak at shorter wavelengths being 9% higher than the other peak. This is similar to the behavior observed in the Balmer line, H_\alpha, in the atomic hydrogen spectrum.
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CHAPTER I
INTRODUCTION

There is considerable interest in the line profiles of spectral lines originating from singly ionized helium. In many plasmas containing substantial amounts of helium, the He II lines are prominent in the emitted spectra. Stellar sources as well as possible fusion devices are expected to contain substantial amounts of helium in the singly ionized state and He II lines with well known line shapes can serve as sensitive density and temperature probes. In the visible and near ultraviolet regions the most prominent He II lines are often He II 3203 (5-3) and He II 4686 (4-3). Accurate knowledge of the shapes of these two lines is therefore important in the determination of plasma conditions.

The broadening mechanisms involved in helium II lines are very similar to those for neutral hydrogen. The states in both species are degenerate in the orbital quantum number and this leads to strong linear Stark effects in the broadening of the emitted lines. These effects, which cause a splitting of the degenerate levels, are caused by the almost static electric fields present at the perturbers due to the slow moving ions that are present in the surrounding plasma. A knowledge of the ion field distribution can lead to accurate ion broadened line shapes. The broadening due to electrons, which has
the effect of mixing the ion shifted and broadened components, however, is not easy to calculate. Various approximations have been made in order to simplify the calculations but errors are often introduced in the final profiles. Therefore experimental measurements of the line profiles are of paramount importance in determining deficiencies in the theories.

The purpose of this investigation was to measure the profiles of the He II lines at 3203 Å and 4686 Å in a well diagnosed plasma and to compare the experimental results to theoretical profiles obtained from different treatments of the electron broadening. The theoretical treatments, one which treats the electron broadening collisions as single event impacts, and the other which considers the time development in the collision process, lead to significant differences in the broadening of the lower levels of the transitions of interest. Since interference between the upper and lower levels can lead to a narrowing of the line, the two treatments of the lower levels lead to differences in the predicted line shapes. The broadening of the lower levels is expected to be a greater effect in the profile of He II 4686 than in the profile of He II 3203. Therefore, a study of both these lines is important in understanding the nature of the deficiencies in the theories.

This report is divided into eight chapters. Chapter
II contains an outline of the general theory of pressure broadening as well as of the approximations made in predicting line shapes. Differences in the two approaches to the electron broadening are mentioned and theoretical profiles are compared. Chapter III is concerned with the construction of the Z-pinch used in the studies and the nature of the diagnostic equipment. The pertinent theory and results for the density measurements are presented in Chapter IV. Results of studies of the uniformity and time development of the axial plasma and of the interaction of the tubes with the plasma are reported. The theory behind the temperature measurements is examined in Chapter V which also includes an analysis of how well the experimental plasma satisfied the requirements of the theory. The effect of the tubes on the electron temperature as well as the uniformity and time development of the axial plasma are also discussed. The analysis of the experimental profiles obtained with an optical multichannel analyzer appears in Chapter VI. The calibration techniques and computer analysis of the measured profiles are also presented in Chapter VI. An account of the plasma conditions in the experimental plasma is given in Chapter VII together with a comparison of the experimental and theoretical profiles of He II 3203 and He II 4686. Conclusions concerning the experimental profiles and reasons for the observed discrepancies in the results are presented in Chapter VIII.
CHAPTER II
SPECTRAL LINE BROADENING THEORY

To help understand the theory of line broadening, a radiating atom may be thought of as a classical oscillator emitting radiation at a carrier frequency, $\omega_0$. The intensity of the emitted radiation decays exponentially with a time constant, $T$, which is related to the lifetime of the excited state. A spectrograph essentially Fourier transforms the emitted radiation and so the resulting spectrum for a single atom at rest with respect to the observer is a Lorentzian with centre frequency, $\omega_0$, and width proportional to $T^{-1}$. This form of broadening which is due to the finite lifetimes of the states involved in the transition is called natural broadening. If the radiating atom is moving the carrier frequency is Doppler shifted. For an ensemble of atoms that are moving with different velocities with respect to the observer, the Doppler shifted profiles superimpose leading to a Doppler broadened spectral line. In this investigation the effects of both natural and Doppler broadening were not significant and can be ignored.

Spectral lines emitted by atoms or ions in a plasma may also be broadened as a result of interactions between the emitters and the ions and electrons present in the plasma. Interactions with the ions cause the carrier
frequency, $\omega_0$, of a given atom to be altered due to the Stark effect which splits and shifts the energy levels of the emitter. If the position of the ions changes slowly during the lifetime of the emitter the resulting line profile is an ensemble average over all possible configurations of ions around the emitter, weighted according to the probabilities of the occurrence of the configurations. This is essentially the quasi-static approximation for ion broadening.

Interactions with electrons can lead to further broadening. The electrons move quickly and interact with the emitter for a few cycles of the carrier frequency. The interactions essentially result in random interruptions in the phase of the carrier signal. The Fourier transform of a carrier wave with its phase interrupted at random times leads to a Lorentzian spectrum with a width proportional to the collision frequency. This method of treating the electron interactions is called the impact approximation. If both ion and electron broadening are important the theoretical profile is obtained by convoluting the two profiles.

In a proper quantum mechanical treatment the resulting line profile (intensity of emitted radiation as a function of frequency), neglecting the effects of self-absorption and reemission, is given by:
where $N_R$ is the number density of the radiators, 
\( \omega_{\alpha\beta} \) is the frequency at the line centre, 
\( |\alpha\rangle \) and \( |\beta\rangle \) are the initial and final states, 
\( \vec{d} \) is the dipole moment of the radiator, 
and \( \rho_\alpha \) is the probability that a given radiator is in state \( |\alpha\rangle \).

Since \( \omega \) is approximately constant over the line width, the factor outside the sum is considered to be a constant. Line broadening then arises from the interaction between the dipole moment of the radiator and the electric fields of the perturbers as a result of collisions.

From the properties of the Fourier transform, the time interval necessary for determining a frequency separation \( \Delta \omega \) is \( \Delta t = 1/\Delta \omega \). For determining a line profile, this time of interest corresponds to the half width of the line and is typically equal to the time between collisions. The radiator is usually considered to be perturbed only for the duration of the collision which is approximately given by \( \tau = \rho/\bar{v} \) where \( \rho \) is the distance of closest approach (impact parameter) and \( \bar{v} \) is a typical perturber velocity. Since the ions are much more massive than the electrons, ion velocities are much smaller than electron velocities. Therefore two cases must be considered. For ions the
duration of the collisions, $\tau$, is usually much greater than the time of interest, $\Delta t$, and so the motion of the ions can be ignored during the collisions. On the other hand, the duration of collisions involving electrons is usually much shorter than the time of interest. Therefore collisions involving ions are treated by the quasi-static approximation while collisions involving electrons are treated by the impact approximation. A quantum mechanical perturbation method is used in both cases. In order to simplify matters, the classical path approximation is often used. This means that the perturbers are assumed to travel along classical paths that are independent of the state of the emitter. Charged perturbers therefore travel along straight lines near neutral emitters and hyperbolic paths near charged emitters. This assumption is a good approximation as long as the impact parameters are much larger than the deBroglie wavelengths of the perturbers and the change in the momentum of the perturbers is small compared to their momentum. It is also assumed that the perturber and the radiator are weakly coupled so that their initial states are independent of each other. This condition is satisfied if the mean interaction energy is much smaller than $kT$ (ie. if broadening collisions are much more frequent than exciting and deexciting collisions) and is a good approximation for a frequency separation, $\Delta \omega$, such that $\hbar \Delta \omega < kT$. 
For the quasi-static case, the electric field as seen by the emitter is constant during the time of interest. The final profile in this case is obtained by calculating the energy shifts in the emitter levels, $\Delta E_\alpha (\varepsilon)$ and $\Delta E_\beta (\varepsilon)$, and the intensities, $| \langle \alpha | \vec{d} | \beta \rangle |^2 \rho_\alpha$, due to the electric field, $\varepsilon$, and then weighting these shifts according to the statistical distribution of electric fields as seen by the emitters. The resulting profile is given by:

$$I_{qs}(\omega) = \sum_{\alpha, \beta} \int_0^\infty | \langle \alpha | \vec{d} | \beta \rangle |^2 \rho_\alpha W(\varepsilon) \delta (\omega - \omega_{\alpha \beta} - \frac{\Delta E_\alpha (\varepsilon) - \Delta E_\beta (\varepsilon)}{\hbar}) d\varepsilon$$

where $W(\varepsilon)$ is the probability distribution of the electric field.

Line profiles due to electron collisions are calculated by averaging over all potentials produced by perturbers passing by with various impact parameters, velocities, and times of closest approach. The collisions are treated as occurring separately in time. This is generally true for the strong collisions but the long distance collisions can never truly be separated in time. However, since the average interaction is weak, to first order even the distant collisions can be treated separately. The resulting profile in the impact approximation is given by:

$$I_1 (\omega) = \frac{1}{\pi} \text{Re} \sum_{\alpha, \alpha', \beta, \beta'} \vec{d}_{\alpha \beta} < \alpha \beta | \left[ i\omega - \frac{i(H_a - H_b)}{\hbar} - \phi_{ab} \right]^{-1} | \alpha', \beta' \rangle \langle \alpha', \beta' | \vec{d}_{\alpha \beta}^*$$

(2-3)
where $d_{\alpha\beta}$ are the dipole matrix elements between substates $\alpha, \alpha', \ldots$ and $\beta, \beta', \ldots$ of two groups of levels, $a$ and $b$.

$H_a$ and $H_b$ are the emitter Hamiltonians which act on the substates $|\alpha\rangle$ and $|\beta\rangle$, respectively, and $\Phi_{ab}$ is an operator that contains time and interaction potential information.

The problem is to evaluate $\Phi_{ab}$. Times are considered that are long compared to the duration of the collisions. Each collision is then treated as a separate event with no time development. $\Phi_{ab}$ is commonly evaluated in terms of S-matrices describing the scattering of the perturbing electron on upper and lower levels. Cutoffs are introduced for large and small impact parameters. The large impact parameter cutoff is of the order of the Debye length and so corresponds to the distance at which screening of the perturber is important. The small impact parameter cutoff is introduced because of a breakdown in the scattering matrices for strong collisions. The effect on the line profile from collisions with impact parameters less than this cutoff is often small and these collisions are treated separately. The overall line profile is then calculated by neglecting the motion of the ions and adding the static ion perturbation to the unperturbed emitter Hamiltonians $H_a$ and $H_b$ in 2-3. The electron impact approximation is then used to find the line shape for these new values of
$H_a$ and $H_b$ and the final line profile is found by averaging over the distribution of ion fields.

$$I(\omega) = \frac{1}{\pi} \int d\tilde{\varepsilon} \, W(\tilde{\varepsilon})$$

$$\times \text{Re} \sum_{\alpha, \alpha', \beta, \beta'} \delta_{\alpha \beta}^{\alpha' \beta'} \left[ i\omega - \frac{i[H_a(\tilde{\varepsilon}) - H_b(\tilde{\varepsilon})]}{\hbar} - \phi_{ab} \right]^{-1} |\alpha' \beta'\rangle \langle \alpha \beta|$$

(2-4)

where it has been assumed that $\phi_{ab}$ is independent of $\tilde{\varepsilon}$.

This expression is valid if the uncertainty introduced by neglecting the ion motion is small compared to the electron impact half width or the distance from line centre, whichever is larger.

For isolated lines such as He I 5876 the matrix elements of $(H_a(\tilde{\varepsilon}) - H_b(\tilde{\varepsilon}))/\hbar$ give the position of lines that are slightly shifted by the quadratic Stark effect. The field dependence can often be ignored, however, since the energy splitting due to the ion field is much less than the energy uncertainty in an electron broadening collision. Therefore the ion broadening results in only a small correction to the electron broadened profile and the final profile is approximately Lorentzian in shape.

For lines from hydrogen and ionized helium where the levels are degenerate with respect to the orbital quantum numbers, splitting of the levels due to ion broadening is important. The ion splitting in this case is by the linear Stark effect (ie. the shift is proportional to the field).
Electron impact broadening then mixes the split levels.

Kepple (1972) has used a classical path impact theory that accounts for perturbations of both upper and lower levels of the radiating ion in order to calculate theoretical profiles of several He II lines. Perturbations due to singly charged ions are treated by the quasi-static linear Stark-effect approximation. Finite duration of collisions and screening of the electron fields are allowed for by calculating the velocity dependence of the maximum impact parameter cutoff. The approximate effect of inelastic collisions (i.e. those collisions that result in a change in the principal quantum number of the radiating ion) is calculated using semi-empirical Gaunt-factors. Terms up to the quadrupole term in the interaction potential multipole expansion are considered in a second order expansion. Resultant profiles of the He II lines at 3203 Å and 4686 Å are given in Figures II-1 to II-4, for various values of density and temperature.

Profiles of He II 4686 have also been calculated by Greene (1976) who has used the unified classical path theory to treat the electron collisions. Ion collisions are still treated quasi-statically. The unified classical path theory unifies aspects of impact, one electron, and relaxation theories to produce a theory that can be used from the line centre to the far line wings. The cutoffs for large and small impact parameters introduced in the
Figure II-1: Theoretical profiles of He II 4686 for various electron densities.
Figure II-2: Theoretical profiles of He II 4686 for various electron temperatures.
Figure II-3: Theoretical profiles of He II 3203 for various electron densities.
Figure II-4: Theoretical profiles of He II 3203 for various electron temperatures.
impact theory are avoided. Relaxation theory is used to reproduce the results of the strong collision cutoff but is valid everywhere besides the line wings. Collisions, in the unified theory, are treated in a time ordered manner (i.e., changes in the direction and strength of the electric field of the electron as it moves by the radiator are considered) as opposed to the nonstructured collisions of the impact model. It is assumed that no two strong collisions occur simultaneously and that the effect of collisions are additive. The resultant profiles for He II 4686 are given in Figures II-1 and II-2. Inelastic collisions were ignored in calculating these profiles and S-matrices were calculated to all orders in the dipole interaction. From the profiles calculated by Kepple and Greene it is apparent that whereas the line profile depends strongly on the electron density, the effect of the temperature on the profile is small.

The profiles predicted by Greene are significantly narrower than those predicted by Kepple. Greene states that the primary cause of this discrepancy is in different ways of treating the broadening of the lower levels. Kepple treats the matrix elements of the electron coordinate vector for the lower level as being real in calculating $\phi_{ab}$ whereas Greene retains their complex form. Since the broadening of the upper levels increases with principal quantum number, the effect of the different treatments of
the broadening of the lower levels on the theoretical line profiles should be less for He II 3203 than it is for He II 4686.
CHAPTER III
EXPERIMENTAL APPARATUS

III-1 The z-pinch discharge

The plasma which was studied in this investigation was produced in a small z-pinch discharge similar to the one used earlier in this lab by Medley (1970). The discharge was formed by passing a high current between two electrodes at opposite ends of a glass tube of 15 cm internal diameter. The current flowed initially along the inner wall of the cylinder and was constricted to the axis by the radial Lorentz force, forming the so-called "pinch". The current was driven by energy stored in a capacitor bank. Plasma conditions could be varied by altering the charging voltage of the capacitors or by changing the filling pressure of the discharge vessel. The plasma produced in this study had quite high electron densities ($\approx 10^{24} \text{ m}^{-3}$) but low temperatures ($< 4 \text{ eV}$).

Plasma parameters have been found to vary considerably with location inside the pinch (Preston (1974)). Therefore observations of spectral lines from extended regions of plasma are often affected by the non-uniformity of the plasma and must be corrected by some form of Abel-unfolding. In order to avoid the problems of unfolding the observed line profiles, the z-pinch used in this study was constructed so as to allow uniform regions of the plasma to be observed.
This was accomplished by means of two collinear quartz tubes that projected into the plasma through slots in the brass electrodes. The tubes were aligned parallel to the axis of the discharge vessel and could be moved along this axis or radially by means of a vacuum tight rack and pinion system in each electrode (see Figure III-1). Each of the tube holders also provided for small vertical and horizontal adjustments in order to allow for accurate alignment of the tubes before the electrodes were evacuated. The tubes acted as limiters so that only light originating from plasma between the tubes was sampled. The tubes had an inside diameter of 61.5mm and were painted black on the inside and capped by quartz windows to ensure that only light originating from between the tubes was accepted. Due to the axial symmetry of the pinch, plasma anywhere within the pinch vessel could be selected by the tubes for study. Uniform columns of plasma were found and studied by varying the separation between the tubes as well as their location inside the vessel.

III-2 The discharge circuit

Figure III-2 shows the general layout of the discharge circuit. The discharge was powered by discharging a 53 μF capacitor bank charged to -12 kV through a triggered spark gap switch (B) in series with the pinch electrodes. Gap B was photon coupled to the triggering circuit in order to eliminate ground loop coupling between the low
Figure III-1: The limiter tube mounts
Figure III-2: The discharge circuit.
voltage triggering and measuring circuits and the high voltage, high current discharge circuit. This photon coupling was accomplished through a trigger pulse generator which produced a spark at the main gap. A thyatron unit was used to produce a small ultra-violet flash which, through ionization of the air between the electrodes of a trigger gap (A) led to the firing of the trigger pulse generator. It was necessary to use the trigger pulse generator since electrode erosion in the main gap can lead to large changes (>1 kV) in the breakdown potential and the u.v. flash could only break down a gap that was less than 500 V below breakdown potential. Since the trigger gap generator was low energy (0.05 μF, ≈12 kV), electrode damage at gap A was much smaller than at gap B and the u.v. flash could be used reliably to initiate breakdown. In order to stabilize the voltage across gap A, the trigger generator capacitor was charged through a voltage divider across the main capacitor bank.

The current from the bank was carried to the pinch electrodes through 10 cm wide flat copper leads. The leads at the pinch were constructed coaxially to lower the circuit inductance as well as to screen out electrical noise. The lead to the ground electrode surrounding the discharge vessel was made of brass gauze to allow side-on observations of the plasma.

A Rogowski coil inserted between the leads to the pinch was used to determine the change in the discharge
current. The discharge current was measured by integrating the output of the Rogowski coil with a passive RC integrator with an RC time constant of 100 μs. This arrangement as well as a typical current trace is shown in Figure III-3. The current waveform was underdamped with a period of 22 μs. The pinch phase (the time at which the current shell stops and much of the discharge current is confined to the axis of the pinch) is indicated by the dip in the trace. The Rogowski coil was calibrated by equating the total charge stored in the capacitors to the integral of the first half cycle of the current trace.

III-3 Optical system for line profile observations

Line profiles were measured by means of the arrangement shown in Figure III-4. Light originating between the tips of the viewing tubes was collected by Lens 1, mounted on the end of the tube projecting through the ground electrode and sent down this tube to Lens 2 which focussed the light onto the entrance slit of the monochromator. The output slit of the monochromator was replaced by an optical multichannel analyzer or OMA. The OMA detector face is divided into 500 individual photodetectors, each with a width of 0.001". It was therefore possible to observe an entire line profile in a single shot. The profile was stored in digital form by the OMA 1205A console and could be displayed on an oscilloscope or recorded on
Figure III-3: A) Circuit for measuring the discharge current  
B) Discharge current waveform
Figure III-4: Experimental arrangement for measuring line profiles.

L₁, L₂: Quartz lenses
M₁: Front surface mirror
S: Stop
a chart recorder. A line to the university computing centre was installed in order to permit the computer calibration and analysis of data. Data stored in the 1205A console was first read and stored in the memory of a small minicomputer. This data was later sent to the computing centre where it was stored in files. The analysis of the data is described in Chapter VI.

It was found that the sensitivity of the OMA was about an order of magnitude less at u.v. wavelengths than it was at visible wavelengths. Thus, although profiles of the helium lines at 4686 Å and 5876 Å could be readily observed, considerable difficulty was encountered in obtaining the profile of He II 3203. The pinch filling pressure and the location of the tubes were dictated by the requirement to make this line as bright as possible. The optics were also arranged to transfer the maximum amount of light to the OMA detector. Lens 2 was chosen so that its effective f-number was close to that of the collimating mirror in the monochromator. This resulted in the use of a large part of the monochromator grating and so optimized the resolution of the instrument. Since the plasma light received by a lens placed outside the pinch vessel would be collected from only a very small solid angle, Lens 1 (f.l.=5 cm) was mounted on the end of the viewing tube to increase the accepted solid angle. The use of this lens rather than a plane quartz window
resulted in a large increase in the amount of light reaching the monochromator.

III-4 Synchronizing the diagnostic equipment to the discharge

For the axial plasma used in this investigation, plasma parameters were found to change on a time scale of the order of 100 ns. To ensure that the plasma conditions changed little during the period of the observations, the OMA was gated by a 200 ns, negative going square pulse. Since the delay between the firing of the thyatron unit and the start of the breakdown in the pinch vessel was about 6 μs, with a shot to shot jitter of about 0.5 μs, the OMA gating pulse could not be synchronized to the discharge through the thyatron unit. Instead, the OMA was synchronized directly to the discharge. This was accomplished by the circuit shown in Figure III-5.

The operation of the 1205A OMA console dictated the actual time at which the pinch fired. Charges accumulated on each of the 500 photodetectors during the time that the gating pulse was applied to the 1205D detector head were read by the 1205A console. The photodetectors were read sequentially every 32.7 ms with a 384 μs dead-time between readings. The pinch was fired and the detector head gated during this dead time. This was accomplished by gating unit #1. The simultaneous closure of the
Figure III-5: Triggering and timing circuit for line profile measurements.
manual firing switch and the reception of the leading edge of a dead-time pulse (from the DELINHD1 output of the OMA console) by gating unit #1 led to the firing of the thyatron unit and the pinch. The resulting current waveform, as measured by the Rogowski coil and RC integrator was then used to synchronize the gating of the detector head to the pinch discharge. This was accomplished through the trigger unit which sent a delayed pulse to the OMA gating unit when the discharge current reached a preset level. The current waveform and the OMA gating pulse were monitored on a two channel scope to determine the time at which gating occurred. Shot to shot jitter was less than 50 ns.

III-5 Measurement of temperatures

Plasma temperatures were determined from the intensity ratio of the lines He II 4686 and He I 5876. The experimental arrangement is shown in Figure III-6. For these measurements two monochromators were used in order to measure the intensities of both lines in a single shot. Mirror 2, in this case, was a beam splitter. The outputs of the photomultipliers were terminated with 880 Ω at a two channel scope. The thyatron unit was fired manually for the temperature measurements. Timing was determined from the scope which was triggered externally by the current waveform (see Fig. III-5, lower half).
Figure III-6: Experimental arrangement for measuring temperatures.
Alignment of the system was accomplished with the alignment laser mounted on a 12' aluminum channel which served as an optical bench. This channel could be moved horizontally, perpendicular to its length so as to keep the optics aligned when the tubes were moved radially. The vacuum system consisted of an oil diffusion and a roughing pump. Purity grade helium was used as the filling gas and the filling pressure was monitored with a manometer and a thermocouple gauge. All important experimental parameters as well as the specifications of the experimental equipment are given in Table III-1.

Results of density and temperature measurements obtained using the apparatus described in this chapter are presented in the following two chapters.
### Discharge Vessel

<table>
<thead>
<tr>
<th>Material</th>
<th>pyrex</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions</td>
<td>length=76 cm; o.d.=17 cm, i.d.=15 cm.</td>
</tr>
<tr>
<td>Electrode separation</td>
<td>60 cm</td>
</tr>
</tbody>
</table>

### Vacuum System

| Mechanical pump | Welch Duo-Seal 1402, pumping speed=90 l/min at 100 μ Hg |
| Diffusion pump | CVC MC275-01, (4" oil) |
| Thermocouple gauge | Varian 801, 0-2 Torr |
| Manometer | 0-15 Torr, contained dibutyl phthalate (ρ=1.047 gm/cm$^3$) |
| Filling system valves | Saunders Edwards Speedivalve Edwards high vacuum isolation valve 05961R |
| Filling gas | helium (purity grade) 99.995% pure |
| Pumping speed | =30 l/min at 0.3 Torr |
| Pump aperture | 1.5" at diffusion pump |
| Base pressure | <1 μ Hg |
| Leak rate | 7 μ Hg/hour |

### Discharge Circuit

| High voltage supply | Universal Voltronics BAL-22kV-35mA |
| Capacitors | 5×10.3 μF, NRG 203 |
| Electrodes | 1/4" brass |
Table III-1 (cont)

Voltage measurement
Conway micro-Ammeter and 25000 HVC Multiplier type B

Inductance of circuit
0.36 mH

Optics

\[ L_1 \]
8 mm, f6.3, f.1.=5 cm (quartz)

\[ L_2 \]
1.5", f1.7, f.1.=6.3 cm (quartz)

\[ L_3 \]
1", f4, f.1.=10 cm (glass)

\[ M_2 \]
=50% beam splitter (glass)

Tubes
length=70 cm, o.d.=8 mm i.d.=6 mm (quartz)

Diagnostic Equipment

Monochromators
SPEX 1800 3/4 m, f6.8 blazed at 7500 Å, dispersion 10 Å/mm
SPEX 1700 3/4 m, f6.8 blazed at 1 μm, dispersion 10 Å/mm

Photomultipliers
\[ P_1 \]
RCA C31034-01 (-1600 V)

\[ P_2 \]
Philips 150CVP (-1100 V)

Termination
880 Ω

Risetimes
0.1 μs

Optical Multichannel Analyzer
Supplier
Princeton Applied Research
Model
1205A
Detector
1205D
Resolution
39 channels/mm
Number of channels
500

Oscilloscope
Tektronix Type 551
Plug-ins
Type 1A1 risetime 10 ns
### Table III-1 (cont.)

**Experimental Conditions**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charging voltage</td>
<td>-12 kV</td>
</tr>
<tr>
<td>Filling pressure</td>
<td>300 mTorr</td>
</tr>
<tr>
<td>Discharge period</td>
<td>22 µs</td>
</tr>
<tr>
<td>Time of pinch phase</td>
<td>4 µs after breakdown</td>
</tr>
<tr>
<td>Time of observations</td>
<td>0.75 µs after pinch phase</td>
</tr>
<tr>
<td>Maximum current</td>
<td>71 kA</td>
</tr>
<tr>
<td>$N_e$</td>
<td>$\left(6.1\pm0.6\right)\times10^{23}$ m$^{-3}$</td>
</tr>
<tr>
<td>$T_e$</td>
<td>$4.0\pm0.4$ eV</td>
</tr>
</tbody>
</table>
CHAPTER IV

DENSITY MEASUREMENTS

In this chapter the theory of Stark broadening of isolated spectral lines is presented. This theory serves as the basis for the density measurements presented later in the chapter. The techniques employed to determine the electron density are discussed and results are presented for the uniformity and time behavior of the axial plasma, as well as for the effect of the limiter tubes on the plasma.

IV-1 Stark broadening of isolated lines

Isolated lines (see Chapter II) are broadened primarily by electron impacts. Ion collisions are much less important and usually result in very small corrections to the impact profile. The ion broadening is usually quasi-static for most laboratory plasmas and can generally be treated by assuming that only quadratic Stark broadening is important although in some cases the effects of quadrupole interactions or linear Stark broadening may become significant. Generally the entire line profile can be found by convoluting the electron impact profiles with the quasi-static, quadratic Stark effect profiles for the ion broadening. The profiles depend on two dimensionless parameters: A (a function of the electron
density), which is a measure of the relative importance of ion broadening, and $R$ (a function of the electron density and temperature), which is a measure of Debye shielding and ion-ion correlations. For values of $A$ between 0.05 and 0.5 and for $R \leq 0.8$, Griem (1974) has given the following expression for the half width half maximum (HWHM) of an isolated line:

$$w_{\text{total}} = w + 1.75A(1 - 0.75R)w$$  \hspace{1cm} (4-1)$$

where $w$ is the electron impact HWHM (a function of the electron density and temperature). Values of $w$, $A$, and $R$ are given by Griem. Corrections to 4-1 to account for multiple ionization had to be made before it could be used to find the electron density.

The effect of ion broadening is often expressed in terms of the normal field strength, $F_0$, which for the case of a plasma containing only singly ionized ions, is given by:

$$F_0 = \frac{2.61}{4 \pi e_0} eN_e^{2/3}$$  \hspace{1cm} (4-2)$$

For a helium plasma containing both singly and doubly ionized ions, the normal field strength becomes:

$$F_0 = F_{01} + F_{02} = \frac{2.61}{4 \pi e_0} [eN_1^{2/3} + 2eN_2^{2/3}]$$  \hspace{1cm} (4-3)$$

where $N_1$ and $N_2$ are the number densities of singly and
doubly ionized ions respectively. Since $N_e = N_1 + 2N_2$, 4-3 can be rewritten as:

$$F_0 = \frac{2.61}{4\pi\varepsilon_0} \frac{N_1^{2/3} + 2N_2^{2/3}}{(N_1 + 2N_2)^{2/3}} e^{eN_e^{2/3}} = \frac{2.61}{4\pi\varepsilon_0} Q_{\text{eff}} e^{N_e^{2/3}}$$

(4-4)

where $Q_{\text{eff}} = \frac{N_1^{2/3} + 2N_2^{2/3}}{(N_1 + 2N_2)^{2/3}}$ is the effective ion charge.

Since ion broadening in isolated lines occurs through the quadratic Stark effect, the value of $A$ in 4-1 should be multiplied by $Q_{\text{eff}}^{3/2}$ to account for multiple ionization. $Q_{\text{eff}}$ was calculated using the Saha-Boltzmann relations assuming total local thermodynamic equilibrium and the result was used in determining the electron density.

IV-2 Experimental details

The study of Stark broadened profiles of spectral lines has long been used as a method for the determination of electron densities. The accuracy of the method depends on the certainty in the theoretical profiles as well as the accuracy of the experimental methods. Since the theoretical profiles of some isolated lines are known accurately, an isolated line was chosen in this investigation to serve as the reference for density measurements. Previous studies[12] of helium plasmas in a similar pinch have used the He I line at 3889 Å for this purpose. It was found, however, that for the axial plasma studied in this investigation, the intensity of He I 3889 was too
small to permit accurate measurements of its profile. A probable cause of this low intensity was the OMA's poor sensitivity at shorter wavelengths. As a substitute, the He I line at 5876 Å was employed in the density measurements. This line is a multiplet but its profile is accurately predicted.

It was found that the intensity of He II 3203 was sufficient for profile measurements only along the axis of the pinch. Therefore all observations of plasma conditions were made with the limiter tubes located along the pinch axis. Preston (1974) had found that the best conditions for spectroscopic observations from the point of view of plasma uniformity occurred at a position 2.7 cm from the axis, but it was found impossible to observe He II 3203 at this position. This was unfortunate since the axial plasma is not as uniform and varies more rapidly with time than the plasma near the region advocated by Preston.

Line profiles of He I 5876 were obtained for various tube positions and separations using the apparatus described in the previous chapter. The OMA was operated in gated mode and the time of observation was kept fixed at 0.75 µs after the pinch phase. The discharge vessel was evacuated and refilled to 0.3 Torr before each shot. At least three shots were fired without refilling before any data were taken. The measured profiles were smoothed
and then corrected for distortions in dispersion and intensity. The system was calibrated for wavelength distortions as well as for the nonuniform response of the OMA by using standard sources (see Chapter VI). Corrections to the measured profiles were performed using the programs described in Appendix 3. The continuum level was found by setting the monochromator to wavelengths 50 Å above and 50 Å below the line centre and obtaining far wing profiles. The wings were then matched to an average main profile and the continuum level estimated. A complete profile of He I 5876 is shown in Figure IV-1. FWHM's were measured for each of the final corrected profiles and densities determined from 4-1 and Griem's data.

IV-3 Interactions of the tubes with the plasma

It was expected that the introduction of quartz tubes into the pinch vessel would perturb the plasma. The magnitude of the perturbation depends, among other things, on the scale size of the plasma and the rates of particle diffusion. Since these parameters are expected to vary in time and with position inside the pinch, it is likely that the perturbations due to the tubes are also variable. An experimental measurement of the effect of the tubes was therefore performed. The tubes were located along the axis of the pinch and their separation was varied keeping the midpoint between their tips coincident
He I 5876

\[ T_e = 4.0 \pm 0.4 \text{ eV} \]

\[ N_e = (6.1 \pm 0.6) \times 10^{23} \text{ m}^{-3} \]

**Figure IV-1: Complete profile of He I 5876.**
with the centre of the pinch. The results are shown in Figure IV-2. Each point was obtained from the average of three shots. The error bars represent standard deviations in any measurement.

The scatter in the data does not permit any strong conclusions to be drawn, but it is apparent from these results that the tubes did influence the plasma column. For tube separations of less than 4 cm, the measured electron density was about 20% less than for tube separations of greater than 8 cm. It is also apparent that for tube separations of less than 4 cm, no drastic changes in the measured electron density occurred with decreased separation. This behavior can probably be explained by the simple model in which each of the tubes perturbs the plasma such that there is a region of uniform, less dense plasma projecting at least 2 cm from the end of each tube. When the tubes are separated by more than 8 cm, regions of unperturbed denser plasma are observed and the resultant profile is a combination of that due to this unperturbed plasma as well as that due to the plasma located near the tubes. For tube separations of less than 4 cm, the perturbed regions overlap and a region of uniform plasma is seen between the tubes. Any additional end effects are likely smaller than 0.5 cm.
Figure IV-2: Effect of the limiting tubes on the electron density.
IV-4 Longitudinal uniformity of the plasma column

In the previous section it was assumed that any changes in the measured electron density were due to perturbations by the tubes and not due to actual variations of the electron density with position along the axis. The uniformity of the plasma column will now be discussed.

Since it was found that the plasma between the tubes was likely uniform for tube separations of less than 4 cm, the tubes were moved along the axis of the pinch with a constant separation of 4.4 cm in order to study the uniformity of the plasma column. The central 12 cm were studied in this way. The results are presented in Figure IV-3. Again the points represent the average of three shots and the error bars are standard deviations. It is apparent from these results that, within the uncertainty of the measurements, the plasma column along the central 12 cm of the axis was uniform with respect to electron density. This conclusion, of course, assumes that the effect of the tubes on the plasma is to decrease the electron density uniformly.

IV-5 Radial uniformity

The uniformity of the axial plasma in the radial direction is also of interest. According to Preston (1974), who studied the pinch dynamics at a filling pressure of 4 Torr, large radial density gradients are present at
Figure IV-3: Longitudinal uniformity of the axial electron density.
the axis when the precursor shock reaches the axis. The axial plasma was found to begin diffusing about 1 µs after the pinch leading to smaller radial density gradients in the vicinity of the axis. Since the observations in this investigation were carried out in 0.3 Torr helium, diffusion rates would be expected to be faster than in Preston's case and the plasma at 0.75 µs may be expected to be quite uniform. Although no direct measurements were made of the plasma characteristics off the axis, results for the uniformity of the plasma in the radial direction can be inferred from interferometric measurements.

An attempt was made to determine the electron density using a Fabry-Perot interferometer to measure the changing refractive index of the variable density axial plasma. The interferometer was similar in construction to that used by Preston (1974). The interferometer had a concentric cavity with the plasma located at the centre. The beam from the alignment laser was used as the probing beam and the cavity was formed between the output mirror of the alignment laser and a 50% dielectric mirror. A monochromator was used to select the laser wavelength from the broad band of plasma light coming from the pinch and a photomultiplier was used to count the fringes. Fringes could be detected on axis only at times greater than 4 µs after the pinch phase. At earlier times no
fringes could be seen due to a drastic attenuation of the probing beam. Medley (1968) also observed this effect for an argon axial plasma at filling pressures of 0.1 and 1.0 Torr. At higher filling pressures fringes could easily be detected on axis during the pinch phase and densities similar to those obtained by Preston were found. An attempt was also made to detect fringes with a Michelson interferometer in which the intensity of the reference beam could be adjusted to compensate for a moderate loss of intensity in the probing beam but almost complete loss of the beam did not allow useful results to be obtained.

This attenuation was thought to be due to refraction of the beam out of the cavity by radial gradients in the electron density but a calculation of the required gradients yielded a result \( 6 \times 10^{24} \text{ m}^{-3}/\text{cm} \) that was much larger than anticipated. The destruction of wavefront coherence in the probing beam, however, can result from much smaller density gradients and can lead to the loss of interference and the attenuation of the probing beam. A lower limit of the density gradients required to cause the loss of wavefront coherence can be calculated.

If a beam of radius, \( a \), passes through a region possessing radial gradients in refractive index, significant loss of phase information occurs if the inner part of the beam travels one half wavelength farther than the outer part:
(n_0-n_a)\lambda = \lambda/2 \quad (4-5)

where \( n_0 \) is the refractive index at the beam axis, \( n_a \) is the refractive index at radius, \( a \), \( \lambda \) is the length of the plasma column, and \( \lambda \) is the wavelength of the probing beam. To first order 4-5 can be written as:

\[ \nabla n a l = \lambda/2 \quad (4-6) \]

Substituting the values appropriate to this study (\( a=0.3 \) cm, \( \lambda=10 \) cm, and \( \lambda=6328 \) Å) we find \( \nabla n=1.1 \times 10^{-5} \) cm\(^{-1}\). For the He-Ne laser line at 6328 Å the relation between the refractive index and the electron density is \( n=1-1.79 \times 10^{-28} N_e \). Therefore the minimum gradient in electron density required to cause complete loss of wave front coherence is approximately \( 6 \times 10^{22} \) m\(^{-3}\)/cm. This gradient should be compared to the electron densities encountered in this study of \( 6 \times 10^{23} \) m\(^{-3}\). If the actual gradients were of about the same size as those predicted above, the plasma column observed in the spectroscopic studies can be assumed to be almost uniform over its diameter. This is especially true since the observations were made after the pinch phase and the plasma had started to diffuse.

IV-6 Time dependence of the plasma

Time variations in the intensity of light emitted by the plasma were found to occur on a time scale of about 100 ns. Two peaks of intensity occurred for the
axial plasma during the first half cycle in the discharge current. The time variations during the first peak were more rapid than those during the second peak and distortions in the observed line profiles during the first peak indicated a very nonuniform plasma column. Therefore observations were performed on the plasma that occurred during the second intensity peak. The time of observation was chosen to be near the time of peak intensity since changes in the plasma parameters were expected to be small over the 200 ns observation time. Profiles of He I 5876 were obtained for times of 100 ns before and after the time of interest in order to determine the time variations in the electron density. The tubes were located 2 cm towards the hot electrode and their separation was 4 cm. The results were:

<table>
<thead>
<tr>
<th>Time (μs after pinch)</th>
<th>Density (×10^{23} m^{-3})</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.65</td>
<td>5.4±0.6</td>
</tr>
<tr>
<td>0.75</td>
<td>6.1±0.6</td>
</tr>
<tr>
<td>0.85</td>
<td>7.6±0.2</td>
</tr>
</tbody>
</table>

The density was therefore increasing slightly during the time of observation and hence, the profiles obtained for He I 5876 as well as the He II lines at 3203 Å and 4686 Å were likely somewhat distorted.

In this chapter it has been shown that the limiter tubes perturb the plasma by lowering the electron density
in their vicinity. For tube separations of less than 4 cm a uniform plasma column can be observed along the central 12 cm of the axis. Nonuniformities in the observed plasma arise from density gradients in the radial direction as well as temporal changes. In the next chapter the results of similar investigations of the electron temperature are presented.
CHAPTER V
TEMPERATURE MEASUREMENTS

Experimental details of the temperature measurements as well as results of these studies are presented in this chapter. These results as well as those of the preceding chapter illustrate the plasma conditions present along the discharge axis soon after the pinch phase. Before describing the experimental details, the theory relevant to the temperature measurements is first presented.

V-1 Theory

For a plasma in some form of thermal equilibrium, the relative populations of atoms or ions in two different excited states can be predicted theoretically. Since the intensity ratio of two spectral lines depends, among other things, on the relative populations of the upper levels of the lines, it is possible to determine the temperature of a plasma by measuring the intensity ratio of two lines. For lines originating from atoms or ions in the same ionization state this method is rather insensitive due to the small separation in energy between the upper levels of the two lines. For lines originating from atoms or ions in successive ionization states, the separation in energy between the upper levels is much larger due to the ionization energy and the ratio of the
line intensities depends sensitively on the temperature.

In order for a temperature to be ascribed to a certain line intensity ratio, it is necessary that the plasma be in a form of thermal equilibrium. A concept commonly used in plasma spectroscopy is that of local thermal equilibrium (LTE). When a plasma is in a state of LTE the population densities of the various quantum states are identical to those for a system in complete thermal equilibrium which has the same temperature and mass density as the actual system. The temperature assigned to the system is that of the species dominating the reaction rates which in most cases is the electrons. Therefore the plasma temperature is often referred to as the electron temperature. When collisional processes with electrons from a Maxwellian distribution dominate over other reaction processes it can be expected that LTE will hold. Since collisional crosssections increase rapidly with principal quantum number while radiative decay rates decrease, LTE will hold only for those states with their principal quantum numbers above a certain value. Systems for which this applies are said to be in a state of partial LTE. Using the criterion that the collisional deexcitation rate is ten times the radiative deexcitation rate, Griem (1964) has estimated the electron density required for the population of the level with principal quantum number, \( n \), to be within 10\% of its value calculated
with Saha-Boltzmann factors from the number densities of atoms in higher levels or higher states of ionization:

\[ N_e > 2 \times 10^{24} \frac{Z^6}{n^{17/2}} (kT_e)^{1/2} \text{ m}^{-3} \]  

(5-1)

where \( Z-1 \) is the charge on the ion and \( kT_e \) is the electron temperature in electron Volts. For the lines studied in this investigation the required electron densities are:

- **He I 5876 (3d-2p)** \( N_e > 3.5 \times 10^{20} \text{ m}^{-3} \)
- **He II 4686 (4f-3d)** \( N_e > 2.0 \times 10^{21} \text{ m}^{-3} \)

These values were calculated for \( T_e = 4.0 \text{ eV} \) which is the temperature encountered in this study. Complete LTE requires a much larger density. For an optically thin helium plasma at 4 eV the required density is about \( 1.5 \times 10^{25} \text{ m}^{-3} \).

In order to estimate the plasma temperature it must be possible to predict the ratio of the densities of the two upper levels of the two spectral lines. Unfortunately, partial LTE for the two upper levels implies only that each of the upper levels is in equilibrium with all higher levels in the same ionization states as well as the ground levels in the next higher ionization states. It does not imply, for instance, that the He II ground state is in equilibrium with the fourth excited state of the He II ion. Therefore complete LTE is usually required at least for the higher ionization state. Fortunately, if
the plasma is optically thick towards the Lyman α resonance line of He II, the electron density required for complete LTE, can be reduced by an order of magnitude. This occurs because the absorption of resonance photons results in an additional contribution to the excitation processes and so the effective radiative population rate of the ground state from the upper state of the resonance line is reduced.

Mewe (1966) has calculated the probabilities that a Lyman α photon will escape from the plasma and has used these probabilities to estimate the values of the factors, \( b_p^{(2)} \), which are defined as the ratio between the actual density of a state with principal quantum number, \( p \), in an ion of charge, \( Z-1 \), and the density predicted by the Saha-Boltzmann relations. The ratio of the intensities of a HeII line, \( a \), with an upper level principal quantum number, \( p \), and a He I line, \( b \), with an upper level principal quantum number, \( q \), is then given by:

\[
\frac{I_a}{I_b} = \frac{2b_p^{(2)}}{b_q^{(1)}} \frac{(gf/\lambda^3)_a}{(gf/\lambda^3)_b} \frac{n_1^{(2)}}{n_1^{(3)}} \exp \left( \frac{13.6}{kT_e} \left( \frac{4}{p^2} - \frac{1}{q^2} \right) \right) \tag{5-2}
\]

where \( g \) is the statistical weight of the lower level, \( f \) the oscillator strength averaged over the fine structure components, and \( \lambda \) the wavelength. \( n_1^{(3)}/n_1^{(2)} \) is the ratio of the densities of completely ionized ions to singly ionized ions in the ground state and is given by:
\[
\frac{n^{(3)}}{n^{(2)}} = \frac{10^6}{b_1^{(2)}} \frac{2g^{(3)}}{g_1^{(2)}} \frac{1}{N_e} \left( \frac{2 \text{ mkT}_e}{h^2} \right)^{3/2} \exp \left( \frac{-E^{(2)}_1}{kT_e} \right)
\]  
\tag{5-3}
\]

where \( E^{(2)}_1 = 52.5 \) is the ionization energy of the ground state of He II. Combining 5-2 and 5-3 and inserting the relevant values for the lines studied:

He II 4686 \( p=4, \ g=18, \ f=0.842 \)

He I 5876 \( p=3, \ g=9, \ f=0.623 \)

the intensity ratio of these lines is obtained:

\[
\frac{I_{4686}}{I_{5876}} = 3.2 \times 10^{28} \frac{b_4^{(2)}}{b_3^{(1)} b_1^{(2)}} \frac{(kT_e)^{3/2}}{N_e} \exp \left( \frac{-52.5}{kT_e} \right)
\]  
\tag{5-4}
\]

Figure V-1 shows the results for the electron densities \( 1.28 \times 10^{23}, \ 6.1 \times 10^{23}, \) and \( 1.28 \times 10^{24} \) \( \text{m}^{-3} \) after interpolating the values of \( b_4^{(2)}, b_3^{(1)}, \) and \( b_1^{(2)} \) given in Mewe's tables. The values of \( b_4^{(2)} \) and \( b_3^{(1)} \) are approximately unity since partial LTE holds for the upper levels. Corrections, however, must be applied to \( b_1^{(2)} \) to account for the escape of Lyman \( \alpha \) photons. Errors in the final ratios are mainly due to errors in the factors, \( b_p^{(2)} \). Mewe estimates the accuracy of the final temperatures to be about 10 to 15%.

For high electron densities \( (=10^{24} \text{ m}^{-3}) \) the uncertainty in the final result is somewhat smaller.

It should be noted that Mewe's results are for a steady, homogeneous helium plasma. While the plasma studied in this investigation can probably be assumed to be fairly
Figure V-1: \( \frac{I_{4686}}{I_{5876}} \) as a function of electron temperature (from Mewe). (d refers to the length of the plasma column)
homogeneous, it can not be assumed to be steady. Changes in the plasma conditions occurred with a time scale of about 100 ns. It is therefore important to consider whether or not the plasma satisfied the criterion of the theory.

The equilibration time for partial LTE above a state with principal quantum number, \( n \), is essentially the inverse of the excitation rate. This time is given by (Griem 1964)

\[
\tau_n = \frac{4.5 \times 10^{13} Z^3}{n^4 N_e} \left( \frac{kT_e}{2 Z^2 E_H} \right)^{1/2} \exp \left( \frac{2 Z^2 E_H}{n^3 kT_e} \right) \text{ seconds} \quad (5-5)
\]

where \( E_H \) is the ionization potential of hydrogen. For the two lines used in this study, \( \tau_4^1 = 9.6 \times 10^{-13} \) seconds (He II 4686) and \( \tau_3^0 = 6.4 \times 10^{-13} \) seconds (He II 5876) for a temperature of 4.0 eV and a density of \( 6.1 \times 10^{23} \) m\(^{-3} \).

The plasma studied was therefore always in partial LTE during the experiments. Total LTE, however, was not always satisfied. For a temperature of 4.0 eV and a density of \( 6.1 \times 10^{23} \) m\(^{-3} \) in a helium plasma, the equilibration time for complete LTE is approximately 0.5 \( \mu \)s. This result is of the same order as the time scale of the experimental plasma. Therefore complete LTE likely did not exist at all times of experimental interest, but due to the logarithmic relation between the line intensity ratio and the temperature, errors in the temperature were likely small.
V-2 Experimental details

Line intensities were measured using the equipment depicted in Figure III-6. Photographs of the intensity traces of the lines He I 5876 and He II 4686, similar to those shown in Figure V-2, were taken and measured to determine the line intensity ratios. The monochromator-photomultiplier arrangements were calibrated for spectral

![Photomultiplier traces](image)

Figure V-2: Typical photomultiplier traces
Top: He II 4686
Bottom: He I 5876

and intensity responses. A movie lamp tungsten coil was used as a black body source to find the spectral response of the optical system. Corrections for the emissivity of tungsten were made using the data of deVos (1954). The
movie lamp was placed between the discharge vessel and the stop, S, and the response of each of the photomultipliers was found for monochromator settings of 4686 Å and 5876 Å. The intensity response was found by setting both monochromators at 5876 Å and measuring the photomultiplier outputs both with the movie lamp and with the actual pinch radiation as the light source. In this way, the difference between the relative intensities reaching the two monochromators in the calibration and in the actual experiment were accounted for. 2.9 mm wide exit slits were used in the measurement of total line intensities. From experimental profiles of the two lines, corrections were calculated for the parts of the profiles cut off by the slits and for the underlying continua.

V-3 Interaction of the tubes with the plasma

As in the case of the electron density measurements, it was expected that the introduction of quartz tubes into the discharge vessel would affect the electron temperature. The effect of the tubes on the measured electron temperature was therefore studied. The tubes were located along the pinch axis and their separation varied keeping the midpoint between their tips coincident with the centre of the discharge vessel. The results are shown in Figure V-3. Each point was obtained from the average of four shots and the error bars represent standard
Figure V-3: Effect of the limiter tubes on the electron temperature.
deviations in any measurement.

As in the case of the density measurements (see section IV-3), the effect of the tubes on the temperature is to lower the temperature in their vicinity. For tube separations of less than 4 cm the temperature was significantly lower than for tube separations of greater than 8 cm. The measured temperature was also found to vary very little with tube separation when the separation was decreased below 4 cm or increased above 8 cm. In Figure IV-4 the raw, uncorrected results for the intensities of the lines He I 5876 and He II 4686 are presented. While these results actually give information only on the number densities of radiators in the two upper states, they also give a rough indication of the number densities of helium atoms and singly ionized helium ions. The intensity of He II 4686 was found to increase linearly with tube separation with a zero intensity intercept at about 6 mm. This indicates that the tubes probably did not affect the number density of He II ions except at distances of less than 3 mm from the tubes. The results for He I 5876, however, indicate an influence extending at least 2 cm from the end of each tube. For tube separations of less than 4 cm the concentration of helium atoms is significantly greater than for tube separations of greater than 8 cm. The non-zero intercept again indicates end effect regions where there is an excess of helium atoms. The situation...
Figure V-4: Intensities of He I 5876 and He II 4686 as a function of tube separation.
suggested by these data is depicted in Figure V-5. The fact that a difference was detected in the density of helium atoms in the perturbed and unperturbed regions while no variation was found in the density of He II ions is explained by the fact that the number density of helium atoms is much more temperature dependent than the number density of He II ions. The variation of the electron density with tube separation discussed in Chapter IV is therefore likely due to small changes in the density of He II ions which could not be detected as well as differences in temperature which affected the concentrations of helium atoms and He III ions.

V-4 Uniformity of the plasma column

Measurements similar to those for the electron density (see section IV-4) were performed to study the longitudinal uniformity of the axial plasma. The tubes were moved along the central 12 cm of the axis of the discharge vessel with a separation of 4 cm maintained between their tips. The resulting electron temperature for various tube positions is given in Figure V-6. The measurements were again made for a time 0.75 \( \mu s \) after the pinch phase. The scatter in the data is large but, within the uncertainty of the measurements, the electron temperature was uniform along the central 12 cm of the discharge vessel. No measurements of the electron temperature
Figure V-5: The suspected effects of the limiter tubes on the observed plasma.
Figure V-6: Uniformity of the axial electron temperature.
were performed for positions off the axis. Preston (1974) had found that for a filling pressure of 4 Torr, no large radial gradients in the electron temperature occurred even for positions along the axis at the time of the pinch. The radial temperature gradients in this study were therefore likely smaller than the density gradients and so, due to the weak dependence of the He II line profiles on the electron temperature, any distortions in the line profiles resulting from temperature inhomogeneities were likely small.

V-5 Temperature time dependence and reproducibility of the pinch

The time history of the electron temperature near the time of interest (0.75 μs) was studied to determine if rapid changes in temperature could affect the measured line profiles. Light traces were obtained for the tubes separated by 4 cm and located 2 cm from the centre of the discharge vessel towards the negative electrode. The results are presented in Figure V-7. It is seen from these results that whereas the density was increasing during the time of interest (see section IV-6), the temperature was almost constant. Therefore distortions in the measured profiles due to changes in the temperature during the 200 ns gating period were small. It was mentioned in section V-1 that the equilibration time for
Figure V-7: Time history of the electron temperature.
LTE at a density of $6.1 \times 10^{23} \text{ m}^{-3}$ and a temperature of 4 eV was about 0.5 µs. Therefore the temperatures determined from line intensity ratios applied to times earlier than those for which the measurements were made and rapid variations in temperature could not be detected. However, this effect probably was not important in this study since the temperature did not change by more than 0.5 eV during times that were of importance in determining the temperature.

It was found that in the measurements of densities and temperatures, shot to shot variations in the pinch characteristics contributed significantly to the uncertainties in the measured plasma parameters. Shot to shot variations in the density as determined from the FWHM of He I 5876 were of the order of 10% while those in the temperature were approximately 3%. The experimental uncertainty in the temperature arose mainly from shot to shot variations in the intensity of He II 4686. These were of the order of 40% while the shot to shot variations in the intensity of He I 5876 were about 10%. The reproducibility of the pinch was found to improve significantly when the pinch vessel as well as the electrodes were cleaned. The poor reproducibility of the dirty pinch was probably due to deposits on the vessel walls leading to changeable initial breakdown conditions. Although the results were fairly reproducible for any given set of measurements, the
day to day variations were quite significant. Both the temperature and the density changed considerably from day to day as can be seen by comparing Figures IV-2 and IV-3 and Figures V-3 and V-6. The reason for these variations is unknown although changes to the discharge circuit due to humidity and deposits of foreign material as a result of the high current discharge are possible explanations.

V-6 Temperature estimate from line to continuum ratios

It is also possible to determine the electron temperature from measurements of line and continuum intensities. Results of theoretical calculations for the ratio of the intensities of both He II 3203 and He II 4686 to the 100 Å wide continuum bands centred at each of these lines are given by Delcroix and Volonte (1973) for various electron densities and temperatures. In the calculations, contributions to the continuum intensity from both neutral and singly ionized helium atoms were considered. The results do not require LTE to be applicable but only partial LTE down to the third principal quantum level in He II. An average profile of He II 4686 was obtained by combining six profiles and the line to continuum ratio measured by graphically integrating the areas under the line and due to the continuum. The resulting temperature, using the data of Delcroix and Volonte, was $3.7 \pm 0.1$ eV which agrees well with the results obtained
from line intensity ratios (4.0±0.4 eV) for the same
tube position and time.

It has been shown in this chapter that the tubes
perturbed the plasma so as to lower the electron temperature.
The central 12 cm of the axial plasma has been shown to
be uniform and time variations in the temperature have
been shown to be small. Results from line to continuum
measurements agreed well with temperatures obtained from
line intensity ratios. From the results of the measurements
of the effect of the tubes on the plasma and of the
uniformity of the axial plasma, a tube separation of 4 cm
and a position 2 cm from the vessel centre towards the
negative electrode were chosen for the final measurements
of the He II line profiles. At this separation the perturbed
plasma regions overlapped and the resulting plasma column
was uniform except for small end effect regions. In
Chapter VII profiles obtained for the He II lines at 3203 Å
and 4686 Å are presented following a discussion in Chapter
VI of the data analysis for the final profiles.
CHAPTER VI
DATA ANALYSIS

An optical multichannel analyzer or OMA was used in this investigation in order to measure the line profiles of the helium lines at 3203 Å, 4686 Å, and 5876 Å. Problems encountered in the use of the OMA as well as methods of calibration will be discussed in this chapter.

Since shot to shot variations in the intensity of the spectral lines studied were as great as 40%, accurate measurement of the line profiles was not possible by shot to shot methods. The OMA permitted the accurate measurement of entire line profiles in a single shot. Shot to shot variations in the electron density which led to changes in the line profiles could therefore be measured independently of changes in the temperature which effected the line intensities but had little effect on the line shapes.

A -900 V square pulse of 200 ns duration was applied to the OMA detector head at the time of interest in the pinch discharge cycle to gate the detector head amplifier stages. The circuit for producing this gating pulse is discussed in Appendix 2. While in real time operation, the response of the OMA was very smooth across all 500 channels and focussing of the image was good, considerable worsening in the sensitivity and focussing characteristics occurred when the OMA was operated in the gated mode.
Therefore, special calibration of the monochromator-OMA arrangement was required.

VI-1 Calibration for intensity response

While the intensity response of any one of the 500 photodetectors was linear to ±1% in both real time and gated modes, the sensitivity from channel to channel was not uniform in gated mode. Therefore profiles obtained in gated mode were distorted and corrections for non-uniform response had to be applied. The intensity response of the OMA in gated mode was found by setting the monochromator to a region in the helium spectrum where only continuum radiation occurred. The pinch was fired as usual and the spectrum of the continuum region obtained at the time of interest. Since the intensity of the continuum radiation was constant over small spectral regions, any channel to channel differences in the measured intensity were due to instrument effects. A typical response curve is shown in Figure VI-1. This curve was obtained for the 130 Å wide spectral band centred at 4800 Å and has been smoothed to remove statistical fluctuations in the recorded intensities. All measured profiles of the He II line at 4686 Å were divided by this curve to correct for instrument distortions in sensitivity. A similar curve was obtained for the continuum region centred at 6050 Å and was used to
Figure VI-1: Sensitivity of the OMA in the region of 4800 Å.
correct the He I 5876 profiles. Since the spectral response of the OMA 1205D detector head changed rapidly around 3200 Å the response curve used to correct He II 3203 profiles could not be obtained from a neighboring continuum region. Instead hydrogen was used as the filling gas and the response curve obtained for the hydrogen continuum region centred at 3200 Å.

VI-2 Calibration of the wavelength scale

Defocussing by the electronics in the OMA detector head in the gated mode was found to lead to blurring of the image as well as wavelength distortions. The real time HWHM of the 6328 Å He-Ne laser line, as measured by the monochrometer-OMA arrangement, was about 1.5 channels. The apparent broadening of this very narrow line was due to electrical crosstalk between adjacent channels of the OMA. When the OMA was operated in gated mode this crosstalk was found to increase. The gating voltage was adjusted to give the best focus and a minimum HWHM of about 4 channels was achieved for a gating pulse of -900 V. Since the dispersion of the Spex 1800 monochrometer was about 10 Å/mm in first order, the instrument HWHM was about 1 Å. Since this instrument profile was roughly Gaussian in shape, the actual width of the helium lines was approximately given by:

\[ w = (w_m - w_i)^{1/2} \]

\[ w_i = \frac{2}{v_m} \]

(6-1)
where \( w_m \) is the measured line width and \( w_i \) is the instrument width. For the line widths measured in this study (HWHM < 13 Å) the contribution due to instrument broadening was only about 0.1 Å. This result was negligible compared to the shot to shot fluctuations (≈10%) in the measured profiles. Wavelength distortions, however, were significant.

A channel dependent shift in the line profiles occurred when the OMA was operated in gated mode. The 6328 Å He-Ne laser line was observed in both real time and gated modes for various monochrometer wavelength settings in the region of 6328 Å and the shift in the gated image with respect to the real time image was measured as a function of the real time position. The wavelength versus channel number scales for monochrometer settings of 3203 Å, 4686 Å, and 5876 Å were found in real time mode using iron arc and Geissler tube sources. From these measurements and the results of the shift measurements, the gated mode wavelength versus channel number scales were determined. This two step procedure was necessary since the iron arc and Geissler tube spectra were too faint to be observed directly in gated mode.

VI-3 Calculation of the corrected line profiles

The corrected line profiles were calculated from the measured line profiles, the intensity response curves,
and the wavelength versus channel number scales using the computer programs described in Appendix 3. The measured line profiles and intensity response curves were first smoothed to remove random channel to channel intensity fluctuations. A smoothing routine was employed which assigned the value of a weighted average of the intensities of several neighboring channels to each of the 500 channels. The amount of smoothing could be controlled by changing the number of neighboring points considered in calculating the weighted average as well as by changing the number of iterations of the procedure. The final corrected profiles were calculated by first dividing the smoothed raw profiles, channel by channel, by the intensity response curves and then by applying the channel number versus wavelength data to determine the wavelength scales. Profiles of He II 4686 before and after the smoothing and correction procedures are shown in Figure VI-2. Both profiles were normalized so that their maximum intensities were 1. The rapid dropoff in intensity at large wavelengths is due to the poor sensitivity of the first 100 OMA channels which could not be corrected for completely.

Since all three lines studied in this investigation were broad, several shots at different monochromometer settings were required to observe the entire profiles. Shots were fired for monochrometer settings 50 Å above
Figure VI-2: Profiles of He II 4686 before (Top) and after (Bottom) smoothing and correction procedures.
and below line centre to obtain the wing profiles. The wing intensities were adjusted to match the intensity of the line centre profile at selected points and the three profiles were joined to form a complete profile. A complete profile of He II 4686 is shown in Figure VI-3. The wings were joined at points 30 Å below and 20 Å above line centre. Although this procedure required several shots to obtain a complete line profile, the important central part of the line was obtained in a single shot. In the next chapter, final profiles of He II 4686 and He II 3203 are presented and compared to theoretical profiles.
Figure VI-3: Complete profile of He II 4686 constructed from three independent profiles.

He II 4686

$T_e = 4.0 \pm 0.4 \text{ eV}$

$N_e = (6.1 \pm 0.6) \times 10^{23} \text{ m}^{-3}$

Joining point

O II 4649

O II 4642

CONTINUUM
CHAPTER VII

LINE PROFILES FOR He II 3203 AND He II 4686

The profiles of the He II lines at 3203 Å and 4686 Å, measured for a well diagnosed plasma region, are presented in this chapter. The experimental profiles are compared to the theoretical profiles of Kepple (1972) and Greene (1976).

The measurements of the final line profiles were made along the axis of the discharge vessel at a position 2 cm from the centre of the vessel towards the negative electrode. Observations were made 0.75 µs after the midpoint in the pinch phase. From the measurements of the effect of the tubes on the electron temperature and density, a tube separation of 4 cm was chosen for the final measurements. At this separation the perturbed regions of plasma surrounding each tube overlapped, resulting in the formation of a uniform plasma column between the tips of the tubes. Local end effects, as indicated by the temperature measurements (section V-3) were probably small and extended less than 0.5 cm from the end of each tube. Profiles of He II 3203, He II 4686, and He I 5876 were obtained in a single series of shots. A total of nine profiles of He II 3203 and six of both He II 4686 and He I 5876 were obtained. The line under study was changed every three shots to reduce the effects of systematic changes in the pinch characteristics.
Wing profiles were also obtained for each of the studied lines.

VII-1 Plasma conditions

The diagnostics described in Chapters IV and V were used to determine the conditions in the plasma that was studied to obtain the line profiles. An electron temperature of $4.0 \pm 0.4$ eV was determined from line intensity ratios for the lines He II 4686 and He I 5876. The quoted uncertainty was due to uncertainties in whether the upper levels of the two lines were in thermal equilibrium with the electrons. Experimental uncertainties were somewhat smaller ($=0.1$ eV). Six profiles of He I 5876 were added together by a computer program in order to average out shot to shot variations in the line shape. An electron density of $(6.1 \pm 0.6) \times 10^{23} \text{ m}^{-3}$ was determined from the FWHM of the resultant profile. The experimental uncertainty was estimated from the scatter in the widths of the six profiles and represents the error in any measurement.

As was mentioned in Chapter V, the plasma studied was not in a state of complete thermal equilibrium. The plasma density was below the value at which LTE is maintained by the predominance ofcollisional processes over other excitation-deexcitation processes. The time scales involved in the studied plasma were also too short for complete LTE to be achieved. The plasma, however, easily
satisfied the conditions for partial LTE. Plasma densities and time scales were several orders of magnitude above those required for partial LTE for each of the spectral lines studied. The lack of total LTE would be expected to be a greater source of uncertainty in the temperature measurements than in the density measurements. Pressure broadening theories do not require complete LTE. A thermal electron distribution is assumed only in calculating the electron impact broadening. This condition was easily satisfied in this investigation since the upper excited states in the He II ions were in partial LTE. Errors, however, may have occurred in the calculation of the static ion electric field distribution since LTE was assumed in calculating the effective ion charge (see section IV-1).

The line profiles predicted by the line broadening theories do not consider the effects of self-absorption of the emitted radiation. Therefore, before the experimental profiles can be compared to the theoretical profiles, the effects of self-absorption must be shown to be negligible.

The optical depth \( \tau \) is given by:

\[
\tau = 8.853 \times 10^{-25} N_\lambda L f_{\lambda u} \lambda^2 S(\lambda) \quad \text{(VII-1)}
\]

where \( N_\lambda \) is the number density of atoms in the lower level of the transition of interest, \( L \) is the length of the plasma column (in meters),
$f_{lu}$ is the absorption oscillator strength,  
$\lambda$ is the wavelength of the spectral line of interest  
in Å,  
and $S(\lambda)$ is the line shape, normalized to unit area.  
The effects of self absorption can be ignored if $\tau$ is  
much less than one.  
Assuming LTE, the population of the lower excited  
state is given by the Boltzmann equation:

$$N_1 = N \frac{g_{1}}{g_{0}} \exp\left(-\frac{E_{01}}{kT_e}\right)$$  
(VII-2)

where $N$ is the population density of the ground state,  
$g_{1}$ and $g_{0}$ are the statistical weights of the lower  
state and the ground state respectively,  
and $E_{01}$ is the excitation energy of the lower level  
above the ground state.

Considering the worst case, which occurs at the line  
centre where $S(\lambda) = 1/\Delta \lambda$ where $\Delta \lambda$ is the FWHM of the transition  
of interest, $\tau$ can be written as:

$$\tau = 8.853 \times 10^{-25} \frac{\lambda}{w} \frac{f_{lu}g_{1}}{g_{0}} \exp\left(-\frac{E_{01}}{kT_e}\right)$$  
(VII-3)

If, as an approximation, we assume that most of the He II  
ions were in the ground state ($N = 6.1 \times 10^{23}$ m$^{-3}$), the  
approximate optical depth for the lines of interest  
in a 0.04 m plasma column were:
He II 3203 $\tau = 1.2 \times 10^{-5}$
He II 4686 $\tau = 1.8 \times 10^{-4}$
He I 5876 $\tau = 3.3 \times 10^{-4}$

Since the optical depth for each of these lines was much less than one, self absorption of the line radiation was not great enough to effect the measured line shapes.

VII-2 Profiles of the spectral lines He II 3203 and He II 4686

Experimental profiles of the He II lines at 3203 Å and 4686 Å are presented in Figures VII-1 and VII-2. The profiles were smoothed and corrected for instrument distortions in intensity and dispersion. The line centre profile for He II 3203 was obtained by adding together eight profiles while that for He II 4686 was obtained from the sum of six profiles. Wing profiles were obtained in a single shot and joined to the line centre profiles at the points shown. The random noise in the profile of He II 3203 was much more evident than the noise in the profile of He II 4686 due to the much smaller measured intensity of the He II 3203 line. The addition of several profiles aided in increasing the signal to noise ratio as well as averaging out shot to shot changes in the line shapes.

Lines due to contaminants were present on the wings of both He II 3203 and He II 4686. The two prominent
Figure VII-1: Measured profile of He II 4686.

He II 4686

$T_e = 4.0 \pm 0.4$ eV

$N_e = (6.1 \pm 0.6) \times 10^{23}$ m$^{-3}$
Figure VII-2: Measured profile of He II 3203.

He II 3203

Te = 4.0 ± 0.4 eV
Ne = (6.1 ± 0.6)x1023 m^-3
lines on the short wavelength wing of He II 3203 were identified as Si IV 3166 and Si IV 3150. The other
bumps in the wings were due to random noise which was more evident in the wings than in the region of the line
centre since the wing profiles were obtained from only one shot. The two lines on the short wavelength wing of
He II 4686 were identified as O II 4649 and O II 4642. The oxygen and silicon contaminants probably originated
from material burnt off the walls of the discharge vessel and quartz tubes.

First order theory predicts that both He II 3203 and He II 4686 should be symmetric about the unshifted line
centre. The experimental profiles were symmetric within experimental uncertainty except in the region of the double
peak in the He II 3203 profile. The blue peak was approximately 9% more intense than the red peak. The
discrepancy was at first thought to be due to contamination lines or poor intensity calibration but experiments
indicated that the effect was real. Checks were performed by adjusting the monochromator wavelength setting so
that the He II 3203 line centre was located at high channel numbers where the intensity response was uniform
(see Figure VI-1) and also by positioning the OMA detector head upside down so the apparent dispersion was reversed.
In both cases the blue peak was still found to be more intense than the red peak.
Previous studies of a hydrogen plasma carried out in other investigations\textsuperscript{[5,15]} have revealed an asymmetry between the two peaks of the $H_\beta$ line which favored the blue peak. A study of the theories reveals several spots at which asymmetries may occur. By considering the $\omega^4$ dependence in equation 2-1, the Boltzmann distribution among the substates of the initial state, and the proper conversion between angular frequencies and reduced wavelengths an asymmetry of about 8% in favour of the blue wing is introduced. However, these corrections only affect the far wings and have little effect in the region of the peaks. Asymmetries in the ion broadening, however, may lead to differences in the peak intensities. These asymmetries arise from higher order (quadrupole etc.) interactions between the radiator and the perturbing ions as well as from quadratic Stark effects. The differences in the intensity of the He II 3203 peaks may be due to these effects.

VII-3 Comparison of the experimental and theoretical line profiles

The experimental profiles of He II 4686 and He II 3203 are compared to the profiles predicted by Kepple and Greene in Figures VII-3 and VII-4. The experimental profiles were obtained from those in Figures VII-1 and VII-2 by subtracting off the continuum levels and normalizing the resultant profiles to unit area. The theoretical profiles
Figure VII-3: The experimental and theoretical profiles of He II 4686.

He II 4686

\[ T_\text{e} = 4.0 \pm 0.4 \text{eV} \]
\[ N_e = (6.1 \pm 0.6) \times 10^{23} \text{m}^{-3} \]
Figure VII-4: The experimental and theoretical profiles of He II 3203.

He II 3203

$T_e = 4.0 \pm 0.4 \text{ eV}$

$N_e = (6.1 \pm 0.6) \times 10^{23} \text{ m}^{-3}$
were obtained by interpolating profiles (Griem (1974), Greene (private communication)) and were calculated for an effective charge of 1.22e and a temperature and density of 4.0 eV and 6.1x10^{23} \text{ m}^{-3} \text{ respectively.}

Comparison of the experimental profile for He II 4686 to the theoretical profiles indicates that the experimental results are somewhere between those of Kepple and those of Greene.

Theoretical data for He II 3203 was only available from Kepple's treatment. Comparison of the theoretical and experimental profiles revealed significant differences in the regions of the line centre and far line wings. For both He II 3203 and He II 4686 comparison between experiment and theory in the line wings should be made for the shorter wavelength wing since the larger wavelength regions have been recorded in the less responsive channels of the OMA. In the following chapter, possible reasons for discrepancies between the theoretical and experimental profiles are discussed and conclusions are presented concerning the plasma conditions.
CHAPTER VIII
CONCLUSIONS

In Figures VII-3 and VII-4 experimental profiles for He II 3203 and He II 4686 were compared to theoretical profiles predicted by an electron impact (Kepple (1972)) and a time evolutionary treatment of the electron collisions (Greene (1976)). The experimental results for He II 4686 were found to lie between the two theoretical profiles. Greene's calculations resulted in a profile with a value for the FWHM 45% less than the experimental result whereas Kepple's calculations resulted in a FWHM that was 40% greater than for the experimental profile. Errors in the estimation of the effect of strong electron collisions on the far line wings were likely the major cause of the discrepancies between the experimental and theoretical profiles. Since the interference between the upper and lower levels of the He II 4686 transition can lead to a narrowing of the line profile, it can be concluded that Greene has probably overestimated the broadening of the lower levels while Kepple's calculations have likely underestimated the effect of the lower levels.

Since the upper level of He II 3203 is broadened much more than that of He II 4686 it is expected that the effect of lower level broadening is of greater importance in determining the line shape of He II 4686 than in the
profile of He II 3203. Therefore agreement between the theoretical and experimental profiles of He II 3203 is expected to be better than for the He II 4686 profile. Unfortunately data for He II 3203 was only available from Kepple's method and so comparison between the two theories was not possible. Comparison of Kepple's predicted line shape with the experimental results for He II 3203 indicated large disagreements in both the shape and the width of the experimental and theoretical profiles. The difference in the peak intensities, as mentioned in the previous chapter, can probably be partly attributed to higher multipole interactions and quadratic Stark effects. However, the disagreements in the line width (the FWHM of the theoretical profile was larger by \( \approx 60\% \)) cannot be fully accounted for. This poor agreement between theoretical and experimental results may indicate that the He II 3203 and He II 4686 lines originated from different plasma regions. However, experimental measurements of the uniformity of the plasma column and of the interaction of the tubes with the plasma suggested that the observed plasma column was uniform in both temperature and density except in very small end effect regions extending less than 0.5 cm from the tips of the tubes. Possible nonuniformities in the observed plasma column due to radial density gradients cannot be considered as an explanation for the observed discrepancies since
the upper levels of He II 3203 and He II 4686 differed in energy by only 1.23 eV and so the lines would be expected to originate from the same plasma regions.

Differences between the experimental and theoretical profiles for both He II 3203 and He II 4686 may have occurred due to errors in the determined electron density. A possible source of error may have occurred in the calculation of the effective ion charge. Total LTE was used in calculating the effective charge but only partial LTE existed. If the value of $Q_{\text{eff}}$ was underestimated then the effect of ion broadening on the profile of He I 5876 would also be underestimated and the determined densities would be too large. The effects of the underestimated effective charge and the corresponding overestimated electron density on the calculated theoretical profiles of He II 3203 and He II 4686, however, would tend to cancel since the theoretical line widths increase with both effective charge and density. Therefore errors in the calculated theoretical profiles due to small uncertainties in the value of the effective charge would be small.

It is possible that the He I and He II lines originated from different plasma regions. Much of the He I 5876 emission may have originated from the small (<0.5 cm) end effect regions in which the plasma temperature and density was less than in surrounding regions (see
Figure V-5). If this occurred, the electron density, calculated from the FWHM of He I 5876, would be smaller than the density of the plasma from which the He II lines originated. The theoretical profiles would then be expected to be narrower than the experimental profiles but, at least for the case of Kepple's profiles, the opposite was true.

Considering these arguments, it seems likely that real discrepancies existed between the theoretical and experimental profiles and these discrepancies were primarily due to deficiencies in the theories.

Concluding Remarks

It has been shown in this study that the limiter tubes may be used to select uniform plasma columns for observation. Plasma conditions along the axis of the discharge vessel were found to be uniform although small radial density gradients likely occurred. Differences between the theoretical and experimental He II line profiles were shown to be mainly due to deficiencies in the theoretical treatments. Improvements in the plasma conditions (i.e. smaller density and temperature gradients and longer time scales) are possible if observations are performed well off the discharge axis and with filling pressures greater than 300 mTorr. Density determinations by means of a laser interferometer should be possible for these plasmas and so errors due to the He I and He II
lines originating from different plasma regions could be avoided. Observations of He II 4686 could be made under these conditions but improvements in the optical and detection systems would be necessary in order to study the He II 3203 profile.


Figure A1-1: The resistive dividers for the photomultiplier dynode chains.

Top: Philips 150CVP
Bottom: RCA C31034-01
APPENDIX 2

THE OMA. GATING CIRCUIT.

The focussing characteristics of the OMA detector head are highly sensitive to the applied gating voltage. To achieve sharp focus it is necessary that the gating pulse rise-times be short compared to the pulse duration.

The schematic diagram of the circuit used to produce short duration high voltage OMA gating pulses is shown in Figure A2-1. Two KN22 krytrons were used to form the pulse. The pulse was initiated when krytron #1 was turned on by a trigger pulse applied to its grid. This trigger pulse was produced by a delay unit connected to the input of the gating circuit. Charge stored in capacitor C1 then flowed to the capacitively coupled OMA detector head through the output pulse terminal and also charged capacitor C2 which was connected to the grid of the second krytron. When C2 was sufficiently charged krytron#2 was turned on and the output to the OMA was shorted to ground. The pulse duration could be adjusted (0.2 to 1.0 µs) by changing the value of C2 and R1 or by altering the supply voltage (provided by a Fluke 412B high voltage power supply).

This circuit differed from previous krytron based gating circuits in that the keep-alive currents were applied to both krytrons at all times. Previous circuits
Figure A2-1: The OMA gating circuit.
were designed so that the keep alive current was applied to the second krytron only after the start of the pulse and so these circuits were incapable of pulses of less than 1 μs duration. A typical output pulse is shown in Figure A2-2. The upper trace was measured with a 10x probe connected directly to the output pulse terminal while the lower trace was measured across the monitor output. The OMA detector head was connected to the output pulse terminal by a 30 cm length of RG-59/U cable. The use of longer cables resulted in ringing in the pulse, probably due to mismatched impedences. The pulse rise-times were measured to be less than 30 ns of which a significant part was probably due to the greater than 10 ns rise times of the Tektronix 1A1 scope preamplifiers.
Figure A2-2: The OMA gating pulse.

(A): Output to OMA
(B): Output from monitor
APPENDIX 3
THE COMPUTER PROGRAMS

The computer programs used for smoothing the measured profiles as well as for correcting for instrument distortions in dispersion and sensitivity are described in this appendix. All the programs were interactive so execution time changes could be made in the smoothing etc.

Smoothing the data

The data received from the 1205A OMA console consisted of 500 signed five digit numbers representing the intensities measured by the 500 photodetectors. The first step in the processing of the data was to apply smoothing routines which removed random channel to channel fluctuations from the raw data. Two smoothing routines were employed. A spline fitting routine was adapted to the data using the library subroutines SPLNFT and SPLN. Standard deviations in the measured intensities could be specified and smoothing was performed by fitting a third order curve to every two adjacent points within the limits of the specified error bars. The neighboring curves were joined and first and second derivatives matched at the joining points. In practice, the amount of smoothing was found to be very dependent on the chosen standard deviations and the routine's erratic behavior made its use
impracticable. A simpler routine was found to be suitable for smoothing the experimental profiles. This routine calculated weighted averages of the intensities from several neighboring channels on both sides of a given channel and then assigned the result to the given channel. The number of channels considered in the average (3, 5, 7, ..., 19) could be specified and the weighting was done according to the formula, \( W = 1 - 0.1(|N - X|) \), where \( W \) was the weight assigned to the intensity of channel \( X \) in calculating the new average intensity at channel \( N \). The procedure was carried out for all 500 channels for which the average could be found. End channels (i.e., those for which the average could not be extended to include the same number of channels of both sides of the given channel) were assigned the intensity of the nearest channel for which the procedure worked. Additional smoothing could be achieved by iterating the procedure several times. The final smoothed profiles were visually compared to unsmoothed profiles to ensure that no important information was lost. In practice a 9 point smooth with 3 iterations was sufficient except for the intensity response curves where 15 point smooths and 7 to 15 iterations were used.

Intensity calibration and correction

The measured profiles were corrected for nonuniformities in the channel to channel sensitivity by first smoothing the intensity response curve obtained for a neighboring
continuum region and then dividing the measured profiles, channel by channel, by the response curve. Normalization of the maximum intensity to a value of one was performed by dividing the intensity at all channels by the maximum intensity.

**Wavelength calibration and correction**

Values of the wavelengths and corresponding gated mode channel numbers, as determined from the wavelength scale calibration measurements, were interpolated using the spline interpolation subroutines SMOOTH and SMTH to find the wavelengths corresponding to each of the 500 channels. The final smoothed and corrected profiles were then plotted.

**Wing fitting**

The wing fitting program performed all of the above mentioned, smoothing and correction procedures for each of the wing profiles as well as for the line centre profile. Each profile was smoothed independently. Distortions in intensity were then removed by dividing each of the profiles, channel by channel, by one intensity response curve. The wavelength scales were then calculated using the wavelength versus channel number data and a spline interpolation procedure. The wavelength scales for the wing profiles were determined by adding the shift in the monochromator wavelength setting to the interpolated wavelengths. Finally, the wing profiles were joined to
the line centre profile at specified wavelengths by adjusting the intensity of the entire wing profiles so that the intensities at the matching points on the wings were identical to the intensities of the corresponding points on the line centre profile.