CLM-P 105

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Preprint

PLASMA CONFINEMENT DURING A PERIOD OF REDUCED FLUCTUATIONS IN ZETA

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ABSTRACT

Measurements of electron density and of the intensity of HeII radiation are used to determine the plasma confinement time during a specific period in a Helium discharge. It is shown that the confinement time during a period of reduced fluctuations in ZETA is considerably longer than at other times in the pulse.

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CONTENTS

1. INTRODUCTION

Recent work (BUTT et al, 1964; 1965) has shown that under certain operating conditions a period of the ZETA discharge is characterised by properties markedly different from the rest of the current pulse. The differences are such as to suggest improved stability and confinement. Particularly significant being the large reduction in fluctuations of the rate of change of current dI/dt, and in the velocity of the turbulence elements (WORT, 1962); the vertical shift of the magnetic centre of the discharge is almost completely eliminated (RUSBRIDGE, private communication). A typical dI/dt trace for a discharge in Helium is given in Fig.1, from which it is apparent that during the middle, 'quiescent period' of the pulse the fluctuations are at least ten times smaller than at other times.

The conditions under which the indications of improved stability occur are qualitatively similar to those predicted as necessary for stability in ZETA (BUTT and PEASE, 1963) namely, a small radial pinch ratio (<1.8) favouring magnetohydrodynamic stability (BURTON et al, 1962) and a high line density ($>5\times10^{17}$/cm length) which tends to reduce the likelihood of streaming instabilities. Consequently, a direct determination of the plasma containment time during this period of quiescence is of major importance.

Measurements obtained in a study of helium discharges which demonstrate a significant improvement in confinement during the quiescent period are described in this paper. Further properties of the quiescent period are detailed in BUTT, et al, 1965 where results of the present experiments are also summarised.

2. PLASMA CONFINEMENT TIME: METHOD OF MEASUREMENT

The plasma confinement time, τ_C, may be defined as

$$\tau_C = N/F$$

where N is the total number of electrons in the plasma at any instant and F is the total flux of electrons from the plasma to the walls. When the ionization stage of the discharge is complete, the density of electrons in the plasma is determined by the competing processes of loss of plasma and injection of material from the walls, and the confinement time τ_c is given by:

$$\frac{1}{\tau_c} = -\frac{\dot{N}e}{Ne} + \frac{Z.C}{Ne} \qquad \ldots (1)$$

where Ne is the electron line density per cm length of discharge, C the number of ions injected from the walls per cm length per sec, and Z is the number of electrons released from each injected ion.

In the present study the electron density as a function of time was measured directly and observations using a normal incidence monochromator and an electrostatic probe furnished measurements from which the injection rate was deduced. This method unlike the spectroscopic method (BURTON and WILSON, 1961) can be applied to discharges whose properties (electron temperature and confinement time) vary throughout the pulse; it is particularly valuable when the first term in equation (1) is dominant so that the injection does not have to be estimated accurately.

3. EXPERIMENTAL: APPARATUS AND DATA

3.1 Arrangement of apparatus

All measurements were made on the ZETA plasma with the experimental arrangement shown schematically in Fig.2. The discharge conditions employed are listed in Table II with the associated results.

3.2 Electron density

The number of electrons in a line of sight (N_s) was measured by means of a modulated path laser interferometer (GIBSON and REID, 1964). In the present experiment two laser beams at wavelengths of 0.63 μ and 3.4 μ were employed simultaneously and the interferograms combined so as to eliminate the effects of mechanical vibration in the interferometer. A typical zebra-stripe interferogram is given in Fig.3 and shows the variation of electron density with time, in this case for a vertical line of sight displaced 6.3 cm from the centre of the torus. Separate measurements were made along five lines of sight in the same cross-section to provide results as shown in Fig.4. Integration of these data furnished the mean variation with time of the number of electrons/unit length of discharge (line density), averaged over a number of discharges for each condition. An example of the line density thus determined is given in Fig.5. Also indicated for comparison is the line density, N_0, corresponding to the initial filling pressure and the line of sight density (N_s) observed for a single discharge in the same sequence.

3.3 Injection of helium

It is shown in Appendix I that the rate of injection of ions, C, may be related to I, the intensity of a selected radiation line, by the expression

$$C = \frac{S_j}{X_j} \cdot I \qquad \ldots (2)$$

in which S_j is the ionization rate of the jth ion and X_j is the corresponding excitation rate.

Under the present conditions the most suitable ion for use in the determination of C is HeII. For the case of an electron density of 10^{14} cm^{-3} at a temperature of 20 eV the ionization time for this ion is about 60 μsec; equation (A-1) will be satisfied at greater times and (A-5) will be valid for containment times in excess of this value. The absolute intensity of the (4686 Å) line arising from level 4 is readily measured and calculations are available (BATES, et al, 1962: McWHIRTER and HEARN, 1963), of the appropriate ratio of ionization rate to excitation rate, which should be accurate to within a factor of two. This ratio is shown in Fig.6 as a function of electron density and temperature. It may be noted that a change in electron temperature from 20 eV to 40 eV results in a variation of less than 35% in the corresponding ionization ratios, so that the electron temperature need be known only approximately.

Experimentally, the intensity of the 4686 Å line was measured using a normal incidence, 1½ metre monochromator (Ebert mounting), calibration of the instrument being effected against a standard tungsten ribbon lamp. Various time profiles of the radiation, compared with the rate of change of current, are given in Fig.7. It may be observed from Fig.7(c) that the initial ionization transient causes saturation of the electronics casting doubt on the validity of the subsequent signal and for this reason a mechanical gate was employed to exclude the initial transient during actual measurements. Results, shown in Figs.7(a) and (b), indicate clearly that during the quiescent period the intensity of the 4686 Å radiation is reduced by some six to eight times and fluctuations in the amplitude of the signal are also smaller. The increase in 4686 Å intensity at the end of the quiescent period is less marked than that of the DI/dt fluctuations.

A standard deviation of 10% in the 4686 Å line intensity was obtained from measurements over ten discharges; reproducibility of the intensity on returning to the same conditions after a period of hours was to within a factor of two.

The curves of Fig.6 are based on the assumption that self absorption of the 4686 Å line does not occur. The conditions for this are discussed in Appendix I(ii) where it is shown that self absorption of the 4686 Å, level 4 line is unlikely since no appreciable population of level 3 is expected. However, an attempt was made to verify experimentally that the plasma is optically thin to this radiation by measuring the variation with starting pressure of the ratio of the intensities of the lines at 4686 Å and 243 Å - both of which arise from level 4. Over a range of initial pressures from 0.2 mtorr to 2.0 mtorr the intensity of the 4686 Å line was observed to vary by a factor of 20 whereas that of the 243 Å line changed by only a factor of 5. This behaviour is in qualitative agreement with equation (A-5) which predicts that in this pressure range the 243 Å line should be subject to self absorption whilst the 4686 Å line should be optically thin. Detailed inspection of the ratio of the lines during the quiescent period is difficult, due to limitations involved in measuring the weak 243 Å line in the presence of high background radiation.

In calculating the injection rate from the observed intensity of radiation the geometric relation (A-8) of Appendix II was used. On the reasonable assumption that the injected material will ionize in a thin radial shell, the factor g was taken as 1.0 and, in accordance with the results of section 3.4 an electron temperature of 20 eV was adopted.

In order to show that the radiation received by the calibrated monochromator is typical of the radiation at all points around the major circumference we have measured the intensity of 4686 Å radiation at a number of points, using detectors consisting simply of a photomultiplier and an interference filter. The various detectors were normalised by dividing the intensity at the time of interest by the initial ionization transient. This is a valid procedure for most of the detectors which had similar radial views, but is less reliable for the one detector which had a tangential view of the discharge. A detector was positioned within a HeII ionization distance of most points on the torus, the results are shown in Fig.8, there is no evidence of any strong localised injection and all the observations are within a factor of two of the value at the calibrated monochromator. Taking into account the various limitations discussed in this section, the overall accuracy of the injection measurement should be to within a factor of two.

3.4 Electron temperature

An approximate value for the electron temperature in the plasma is required for determination of the injection rate by the method described above. This was obtained by measurements with a hooded electrostatic probe (GIBSON and MASON, 1962). The probe was situated with its entrance aperture 2.5 cm inside the convolutions of the torus liner, and was oriented so as to furnish maximum signal during the period of the discharge under observation. (This position corresponds to the magnetic field being normal to the analysing grid of the probe.) The electron current to the probe was integrated over specific intervals during the discharge and the electron energy determined by use of an analysing grid. The energy resolution was approximately 1 eV. Although large fluctuations of the signal were observed from shot to shot the results when averaged over 10 to 20 shots exhibited the exponential dependence of electron current on grid potential expected for a Maxwellian distribution. Values of the mean energy and also the electron density at the probe deduced from these measurements are given in Table 1 for the following discharge condition,

Starting pressure of helium	:	1 mtorr
Gas current	:	370 kA
Toroidal magnetic field (B_z)	:	600 G

The conductivity electron temperature estimated for this condition is also shown in Table 1 for comparison. Essentially the same estimate was obtained for all other discharge conditions employed.

TABLE 1

	Period up to peak current (0.1 → 1.6 msec.)	Including quiescent period (2.0 → 3.5 msec.)
Electron density at wall (N_o/cm^3)	$(4.6 \pm 0.4) \times 10^{13}$	$(9.5 \pm 0.5) \times 10^{12}$ †
Line electron density from interferometer (N_o/cm length)	2.5×10^{17}	5×10^{17}
Electron temperature at wall (eV)	24 ± 4	22 ± 2 †
Conductivity temperature (eV)	20 ± 5	27 ± 7 *

† Statistical errors based on the shot to shot variation

* Errors estimates based on uncertainties in the parameters of the model used for calculation.

4. PLASMA CONFINEMENT TIME : RESULTS

A complete set of data pertaining to a single discharge condition in helium is presented graphically in Fig.9. Similar data obtained over a series of discharges at each of a number of conditions which show quiescent periods are summarised in Table II. The errors associated with the measurement of N_e and dN_e/dt are given and, in accordance with section 3.3, it is assumed that the estimate of injection rate is uncertain by a factor of two. The confinement times and associated error calculated from equation (1) are listed in columns 5 and 6.

TABLE II

Condition	Line density N_e electrons/cm length $\times 10^{17}$	$-\frac{dN_e}{dt}$ e's/cm length/sec $\times 10^{20}$	Injection rate e's/cm length/sec $\times 10^{20}$	Confinement time τ_c msec	Possible error range τ_c msec	τ_B msec
1 mtorr He I_{GAS} = 370 kA B_z = 600 G end Q.P. 2.5 → 3 msec (see Fig.9)	3.7 ± 0.35	5.3 ± 1.0	2.3	0.5	0.3 → 0.7	4.1
1 mtorr He I_{GAS} = 410 kA B_z = 900 G beginning Q.P. end Q.P.	4.8 ± 0.5 3.3 ± 0.5	0.5 ± 0.6 3.9 ± 0.6	2.7 3.2	1.5 0.5	0.7 → 4.4 0.3 → 0.8	5.4
1.5 mtorr He I_{GAS} = 440 kA B_z = 900 G beginning Q.P. end Q.P.	7.5 ± 0.65 5.0 ± 0.9	1.0 ± 1.4 8.6 ± 1.6	4.1 5.2	1.5 0.4	0.7 → 5.8 0.2 → 0.7	5.6
2 mtorr He I_{GAS} = 500 kA B_z = 1050 G beginning Q.P. end Q.P.	9.5 ± 0.7 7.8 ± 0.9	-0.3 ± 2.0 8.7 ± 1.9	5.3 5.3	1.9 0.6	0.7 → 3.4 0.3 → 0.9	6.4

In general the present method could not be applied to determinations of confinement time outside the quiescent period. In the pre-quiescent period injection predominates over the rate of fall of electron density and furthermore, measurement of the injection rate is complicated by the tail of the initial ionization transient. After the quiescent period measurement of the rate of fall of density is difficult, because the density itself is considerably reduced and severe mechanical vibration is present in the interferometer. An estimate of the confinement time during the pre-quiescent period was obtained by applying the spectroscopic method of BURTON and WILSON (1961). The addition of 2% of argon to a discharge under conditions similar to those of line one, Table II permitted measurements on the ions argon IV to argon VIII. Possible injection of argon during the experiment was not taken into account but appeared to be small as has been reported previously (BURTON and WILSON, 1961). The confinement time thus determined was 105 ± 5 μsec. This value is in agreement with the value of 125 μsecs previously measured (BURTON and WILSON, 1961) for discharges in hydrogen and deuterium at the same value of the scaling parameter ε, the energy input/unit mass of gas (in this case equal to 2.5 keV/proton mass of which 20% is lost by radiation).

5. DISCUSSION

The plasma confinement time in helium discharges in ZETA, as shown in Table II, ranges from 0.4 msec at the end of the quiescent period to 1.9 msec at the beginning. These values are 4 to 19 times longer than those observed in the period of strong fluctuations which precedes the quiescent period. This result is compatible with section 3.4 where it is shown that the electron density at the walls is five times smaller during the quiescent period than during the prior period, whereas the electron line density increases by a factor of two.

The measured particle containment time may be compared with the energy replacement time, t_E (BURTON et al, 1963):

$$t_E = \frac{3/2[N_e\ T_e + N_i\ T_i] \times 1.6 \times 10^{-19}}{\alpha\ I^2\ \Omega}$$

N_e and N_i are electron and ion line densities
T_e and T_i are electron and ion temperatures in eV
α = fraction of input energy not radiated (~ 0.8)
I = gas current (amps)
Ω = resistance/unit length (ohms/cm)

We assume during the quiescent period that the effective average temperatures are $T_e = T_i = 30$ eV and calculate Ω for this temperature, then

$$t_E \simeq 200\ \mu\text{sec.}$$

Thus the ratio of the electron confinement time to t_E during the quiescent period is about 5, as compared to a ratio of 3 to be expected if the plasma is lost to the wall through a thermal sheath.

A comparison of the present results may be made with published data from other closed lines of force systems. BISHOP and HINNOV (1965) have shown that for the model C stellarator, the confinement time is given by the Bohm law:

$$\tau_B = \frac{r^2 B}{25T} \cdot 10^{-6}\ \text{sec} \qquad \dots (2)$$

where B is the magnetic field in gauss, T the electron and ion temperature in eV and r the plasma radius (cm). In other experimental conditions (PEASE et al, 1966) the containment time was two times longer.

Other stellarators (AKULINA et al, 1965: D'ANGELO et al, 1963) give times in agreement with equation (2). The containment time in the Tokomak (ARTSIMOVICH, et al, 1965) can be interpreted as being two times the value inferred from equation (2), although this result is very sensitive to the assumed discharge radius. Finally for an $\ell = 2$ stellarator with ceasium plasma (ECKHARTT et al, 1965) a containment time has been reported which is twenty times the value predicted by equation (2).

The present results can be compared with equation (2) by assuming that τ and B are the radius of the current channel and the mean value of the magnetic field inside it. The values of τ_B on this basis are given in Table II; they are about four times longer than the most probable values observed at the beginning of the quiescent period.

6. CONCLUSIONS

We have shown that the confinement time during a period of reduced fluctuations in ZETA is approximately ten times longer than that during the preceding period of strong fluctuations. These observations imply that an initially unstable discharge is able to relax into a more stable configuration. The observed confinement times at the beginning of the quiescent period are of the same order as the duration of the period (about 1 msec) and are approximately four times shorter than the Bohm confinement time.

7. ACKNOWLEDGEMENTS

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APPENDIX I

SPECTROSCOPIC DETERMINATION OF INJECTION RATE

(i) Injection rate in terms of line radiation intensity

The ionization of impurity or injected ions in a fully ionized plasma may be described by the following equations:-

$$\frac{dn_1}{dt} = C - n_e\, n_1\, S_1 - \lambda_1\, n_1$$

$$\frac{dn_2}{dt} = + n_e\, n_1\, S_1 - n_e\, n_2\, S_2 - \lambda_2\, n_2$$

$$\vdots \qquad \vdots \qquad \vdots \qquad \vdots$$

$$\frac{dn_j}{dt} = + n_e n_{j-1} S_{j-1} - n_e\, n_j\, S_j - \lambda_j\, n_j$$

where C is the injection rate in ions/cm^{-3}, n_j is the ground state population density of the jth ion, S_j the ionization rate of the jth ion, n_e the electron density and λ_j is the loss rate of the jth ion.

On summation to the jth ion:-

$$C = n_e\, n_j\, S_j + \frac{d}{dt}\left[\sum_1^j n_i\right] + \sum_1^j \lambda_i\, n_i$$

It is assumed that injection is into the atomic state, recombination is negligible and the electron temperature is uniform throughout the volume.

At times longer than the ionization time of the jth ion,

$$n_e\, n_j\, S_j \gg \frac{d}{dt}\left[\sum_1^j n_i\right] , \qquad \ldots \text{(A-1)}$$

and for sufficiently low ionization levels

$$n_e\, n_j\, S_j \gg \sum_1^j \lambda_i\, n_i \; ; \qquad \ldots \text{(A-2)}$$

then the rate of injection is given by

$$C = n_e\, n_j\, S_j \; .$$

In the case of a line arising from the jth level of the ion an excitation rate coefficient may be defined such that the intensity is given by:-

$$I = n_e \, n_i \, X_j \text{ photons cm}^{-3} \text{ sec}^{-1} \qquad \ldots \text{ (A-3)}$$

thence

$$C = \left[\frac{S_j}{X_j} \right] . \, I \; . \qquad \ldots \text{ (A-4)}$$

Furthermore, if for that line

$$(V_I - V_E) \ll kT_e \; ,$$

where

$$V_I = \text{ionization potential} \; ,$$

$$V_E = \text{excitation potential} \; ,$$

and

$$k = \text{Boltzmann's constant} \; ,$$

then the ratio $\left[\frac{S_j}{X_j} \right]$ is a slowly varying function of electron temperature.

(ii) <u>Self Absorption of line radiation</u>

An essential condition for the validity of Fig.6 is that the radiation should not be absorbed in the plasma.

A line will be optically thin (MITCHELL and ZEMENSKY, 1961) if

$$N_s < 40 \, \frac{\Delta\nu}{f} \; , \qquad \ldots \text{ (A-5)}$$

where N_s is the number of ions cm^{-2} in the lower state, in the line of sight, $\Delta\nu$ is the frequency width of the line and f is the absorption oscillator strength.

In the present experiment the 4686 Å line width (due to Stark broadening) has been measured as 2 Å. Accordingly, $\Delta\nu$ may be taken as 3×10^{11} c/s and f is approximately 0.8, the critical population of the level 3 line is

$$N_s = 1.4 \times 10^{13} \text{ ions cm}^{-2} \qquad \ldots \text{ (A-6)}$$

The actual population of level 3 of the HeII ion under the present experimental conditions may be deduced as follows. Assume that injection into the ground state of HeII occurs at the rate given in Table II (2×10^{20} ions/cm length/sec) and that loss from the state is determined by the ionization time of the ion (60 μsec) then the number of HeII ions in the line of sight is

$$N_{II} = 1.3 \times 10^{14} \text{ cm}^{-2} .$$

From the tables of McWhirter and Hearn (1963) it may be estimated that the ratio of level 3 to ground state population will be less than 5×10^{-4} thus the number of ions in level 3 in the line of sight is obtained as

$$N_s < 6 \times 10^{10} \qquad \text{... (A-7)}$$

which easily satisfies equation (6).

APPENDIX II

RADIATION GEOMETRY

Equation (2) may be expressed in the form

$$\frac{C_T}{I_T} = \frac{(4\pi^2 d^2)}{A} \cdot \frac{S_j(T_e)}{X_j(T_e)} \cdot a.g. \qquad \ldots \text{(A-8)}$$

where C_T is the injection rate of ions per cm length of the discharge. I_T the intensity in photons cm^{-2} at the entrance aperture of the monochromator, A the area subtended at the centre of the discharge by the monochromator, d the distance from the centre of the discharge to the entrance aperture and a the discharge radius. The final factor, g, is given by

$$g = \frac{\int_o^a n_e(r) \cdot n_j(r) \cdot r\,dr}{\int_o^a n_e(r) \cdot n_j(r) \cdot dr}$$

Values of g under various assumptions are given below:-

Assumption	g
Uniform n_e and n_j over discharge	0.5
$n_e(r) = n_{eo}(1-r/a)$; $n_j(r) = n_{jo}(r/a)$	0.5
n_j non zero only in shell of radius a, thickness Δ	1.0

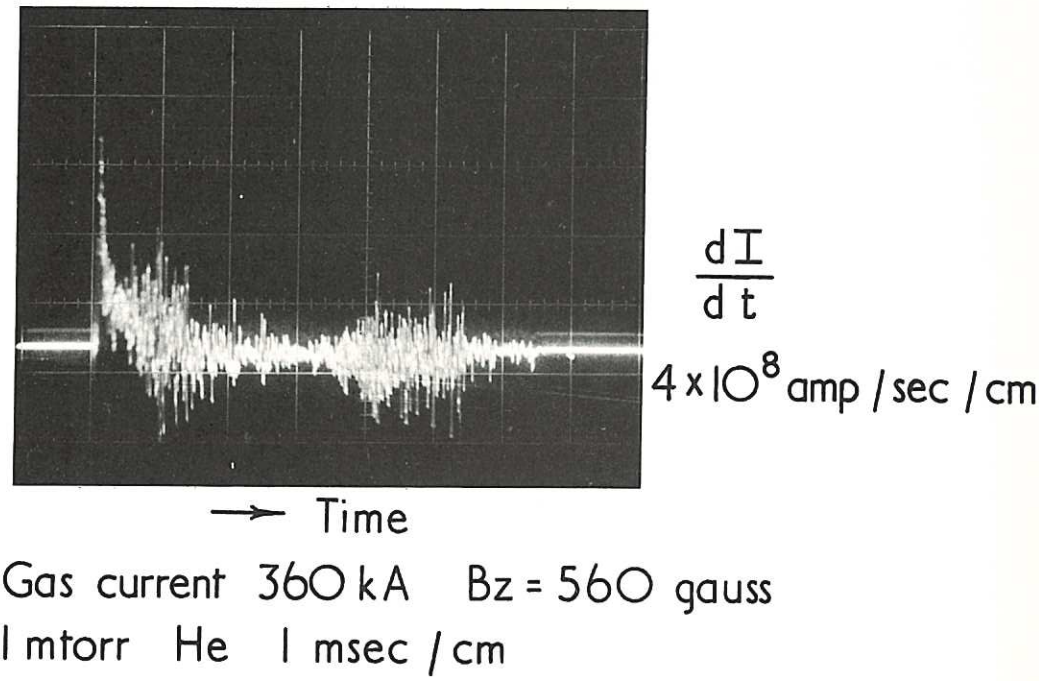

Fig. 1 dI/dt for He discharge showing quiescent period (CLM-P 105)

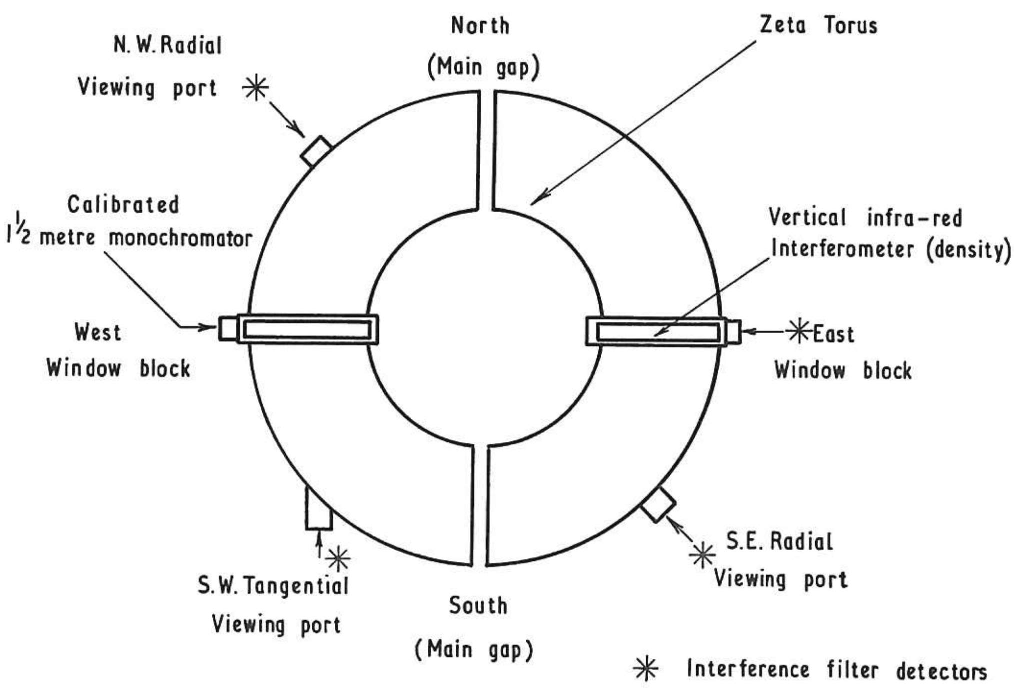

Fig. 2 Experimental arrangement (CLM-P 105)

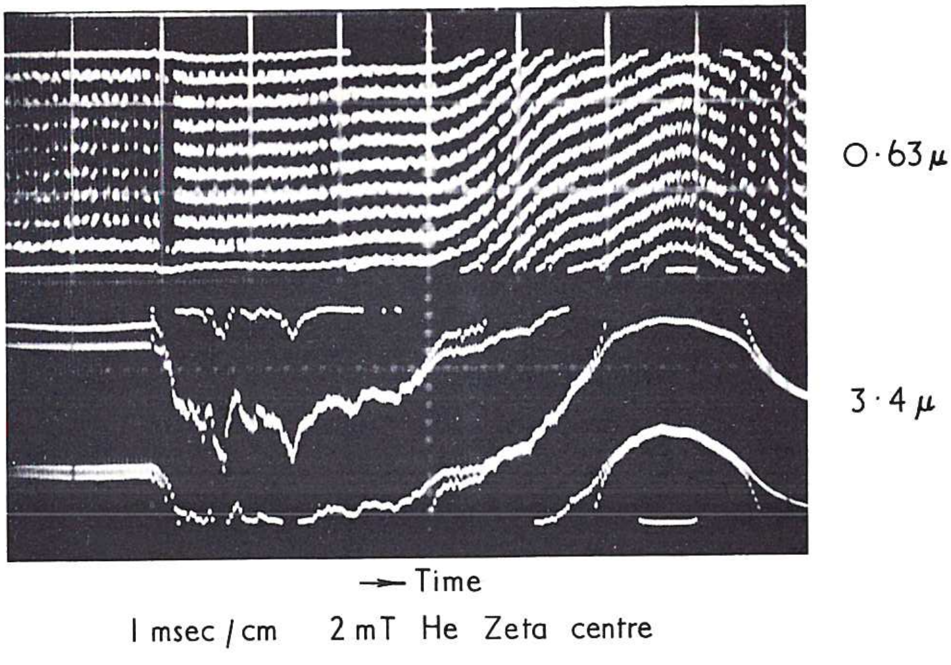

Fig. 3 Infra-red interferometer record (CLM-P 105)

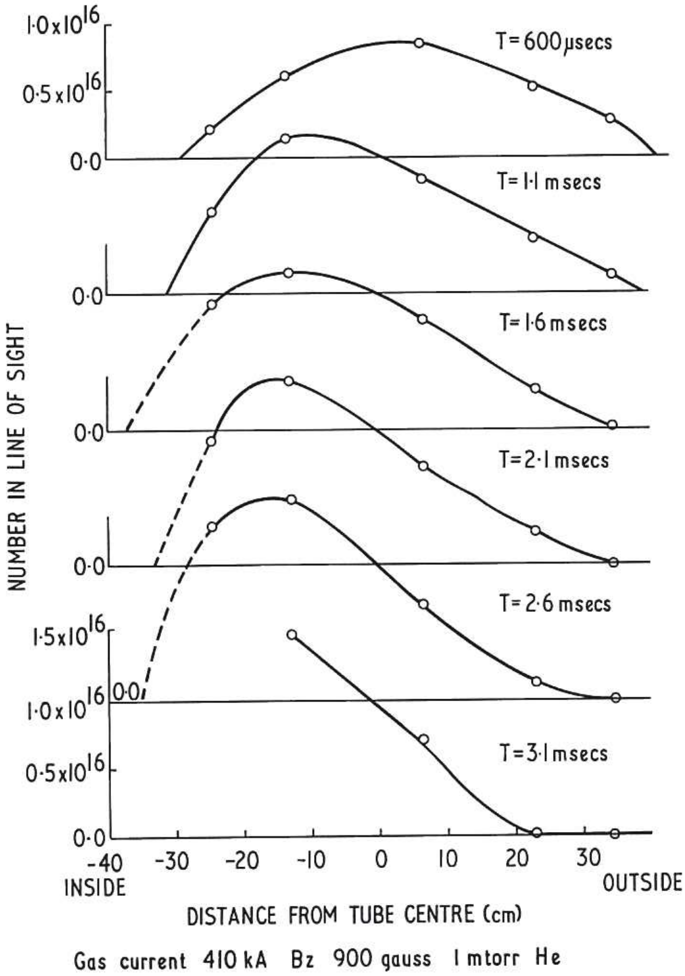

Fig. 4 Electron density along five lines of sight (CLM-P 105)

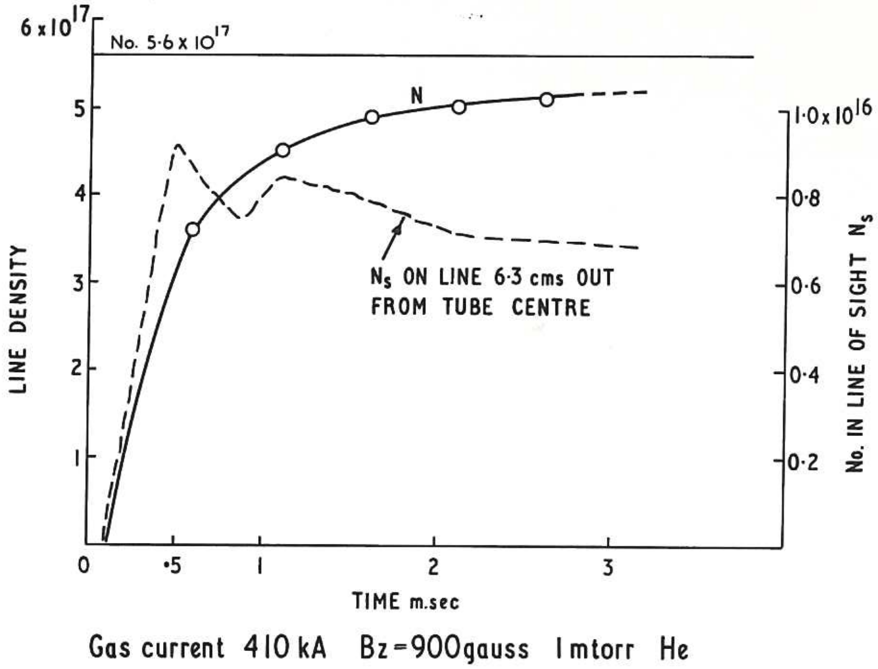

Fig. 5 Line density versus time (CLM-P105)

The number of ionizations of He^{+} to He^{++}_{o} for each (photon) radiated at λ 4686 Å.

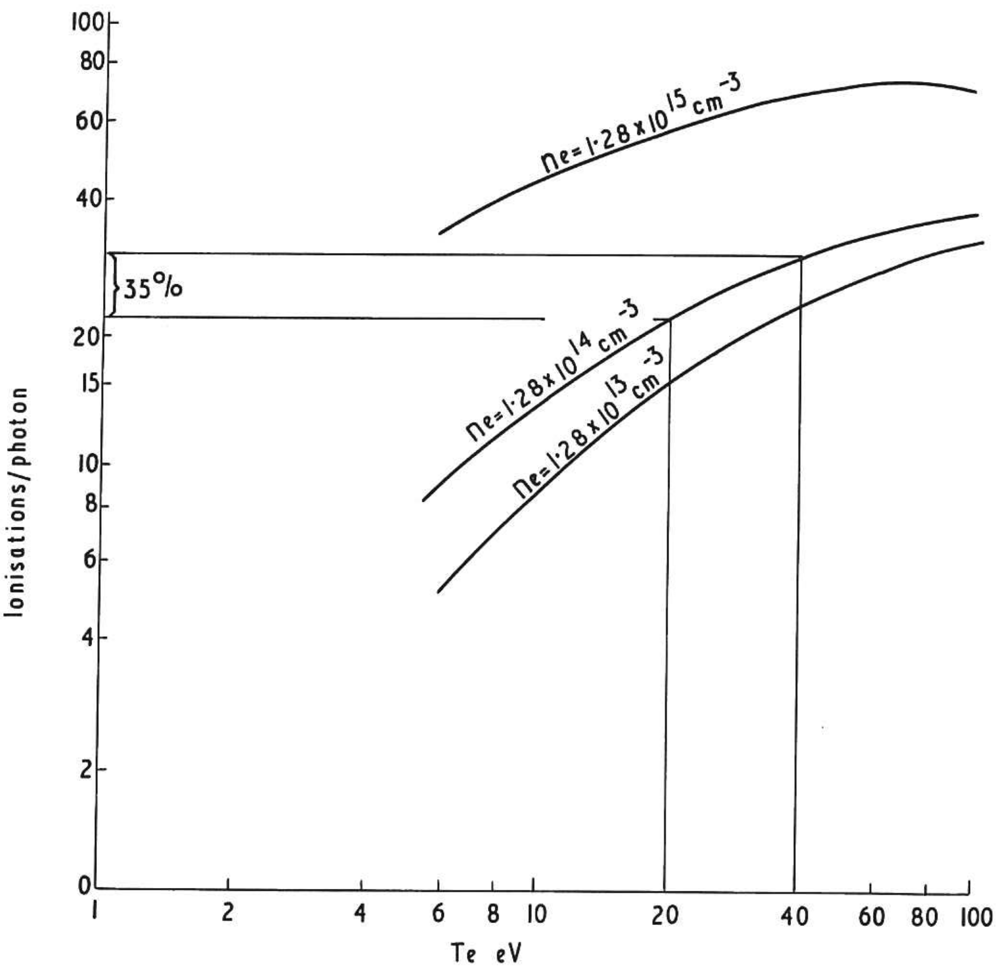

Fig. 6 S/X versus T_e and n_e (CLM-P105)

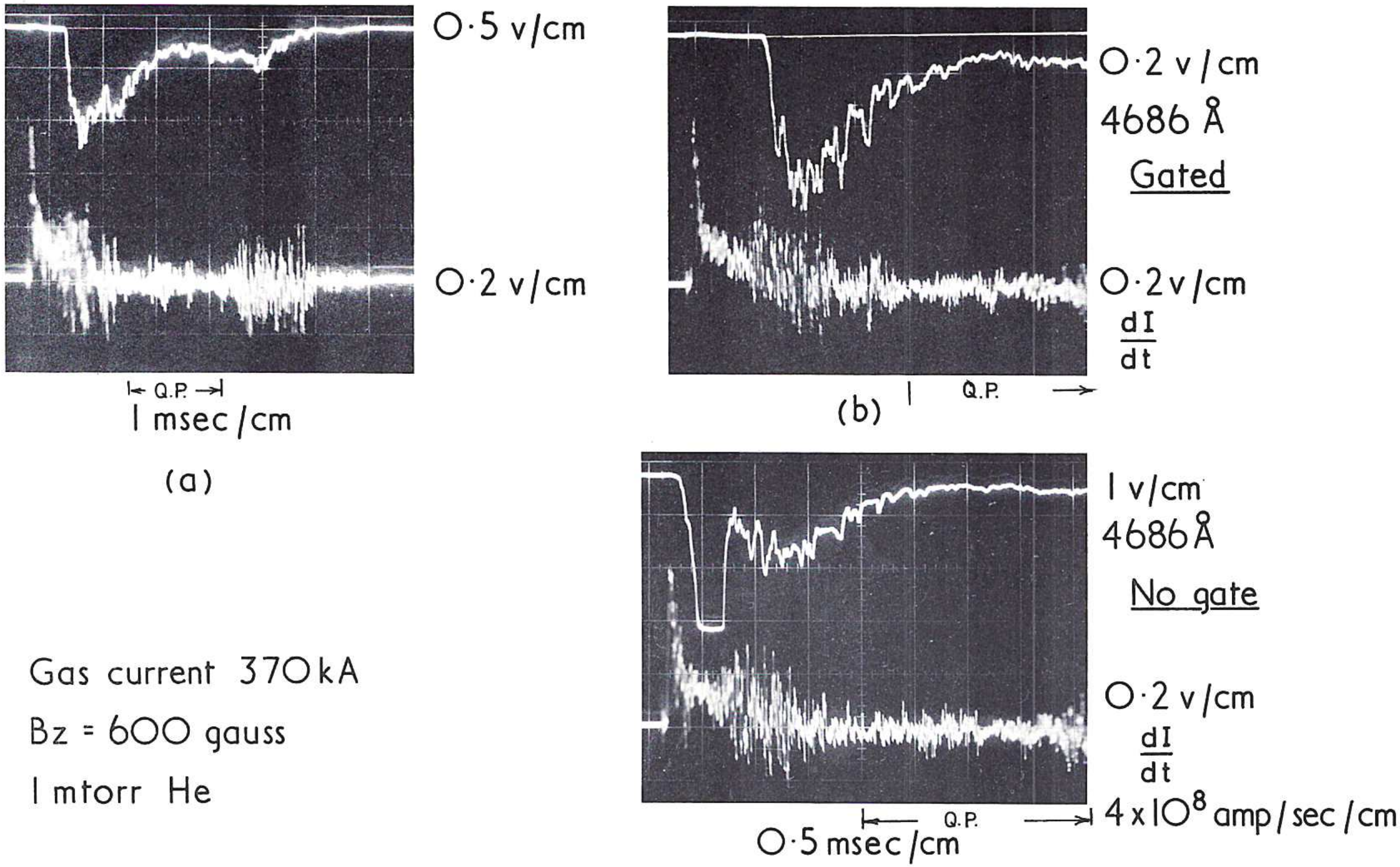

Fig. 7 4686 Å time profiles (CLM-P 105)

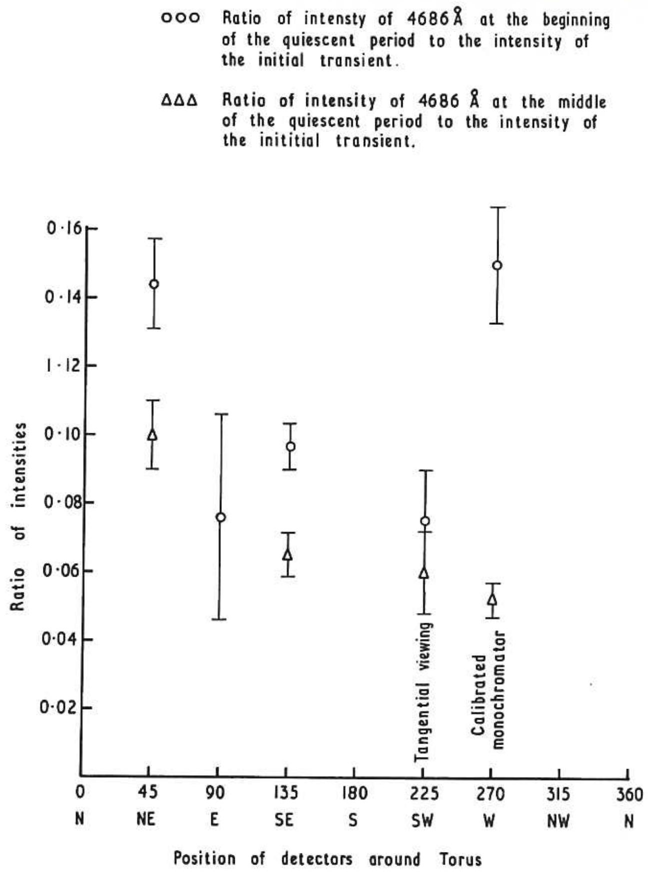

Fig. 8 (CLM-P105)
Variation of 4686 Å intensity with position around major circumference

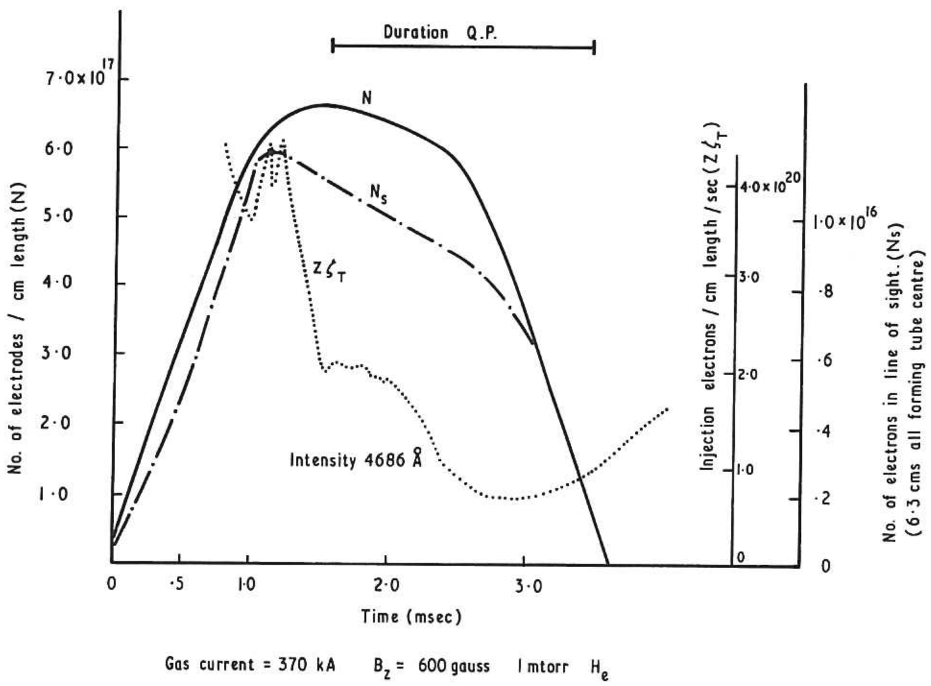

Fig. 9 A complete set of data (CLM-P105)