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Line broadening studies in low energy plasma focus

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Abstract. Optical emission spectroscopic studies were carried out to characterise the plasma leading to the estimation of two plasma parameters, electron density and temperature. These experiments were conducted on a 2 kJ plasma device which is equipped with squirrel cage electrode configuration enclosed in a glass vacuum chamber filled with hydrogen at a pressure of 5 mbar. Spectral emissions obtained from each flash were photographed in the region of 4000–6000 Å using one metre Czerny-Turner spectrograph cum monochromator. Detailed examination of the observed features showed that the H_β and H_γ lines of hydrogen showed significant broadening of the order of 35 Å FWHM which is due to Stark effect expected in high density plasmas. Further several atomic lines of Cu and Zn from the electrode material (brass) showed broadening which was due to quadratic Stark effect. A comparative study of the broadening of lines obtained in DC arc, hollow cathode and plasma focus was made. Electron density from Stark broadened hydrogen lines and quadratic Stark Coefficient C_4 for the CuI and ZnI lines were evaluated. The excitation temperature was determined from the line intensity ratio method using CuI lines.

Keywords. Plasma focus; electron density; Stark broadening; Doppler effect; quadratic Stark effect.

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1. Introduction

One of the potential applications of spectroscopy is in understanding the atomic processes in astrophysical plasmas by providing valuable data from the laboratory experiments. Thus spectroscopy has been playing an important role as a diagnostic tool in plasma physics for quite some time. The basic difference between conventional atomic spectroscopy and plasma spectroscopy is that in the former the interest is mainly related to the study of the atomic structure of an isolated atom while plasma spectroscopy involves not only the study of the electromagnetic radiation emitted by the isolated radiating species but also the properties of the plasma in the immediate environment of the radiator. Recent advances in plasma physics based on sophisticated technology resulted in the development of plasma devices such as laser produced plasmas (inertial confinement fusion), Tokamak discharges, high density Z-pinches

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etc. Further, most of these plasmas are transient and time dependent in nature in contrast to the steady state astrophysical plasmas. Consequently there is considerable development in the spectroscopic techniques to cater to the requirements of plasma diagnostics. A large number of plasma parameters like electron temperature, electron density, impurity concentration, velocity distributions etc can be deduced using the spectroscopic techniques. These aspects have been described in detail in the review articles by Cooper (1966), Weisheit (1981) and De Michelis and Mattioli (1984).

Electron density is an important parameter in plasma physics which can be derived from the spectral line shapes influenced by the electric fields from electrons and ions in a plasma. It is well known (Griem 1964) that the observed broadening of a spectral line in a plasma is due to Stark (sometimes called pressure) broadening, Doppler broadening and natural broadening. In experimental studies, the instrumental broadening also must be considered. In the plasma the emitting atoms and ions experience interaction due to electric fields associated with the plasma electrons and ions resulting in Stark broadening. Knowledge of the Stark broadening of the spectral lines directly yields and the value of the electron density. Another important factor which causes line broadening is Doppler effect which is due to either thermal or directed motion of the emitting ions. For thermal motion, the resulting broadening has a Gaussian shape with half width proportional to the square root of the emitter temperature. Natural broadening is due to the finite lifetime of excited state and yields a dispersion (Lorentzian) profile. In laboratory plasmas this is always negligible (except for autoionisation broadening of doubly excited states). Hence the shape of a spectral line emitted in a plasma is important as it contains information concerning the environment of the emitting atom or ion.

The subject matter of the present paper is related to the study of the spectral line shapes of H_β and H_γ lines of hydrogen, and several lines of copper and zinc emitted from plasma focus. From the Stark broadened half widths of H_β and H_γ lines the electron density (n_e) is evaluated. Similar studies on the line broadenings of the electrode material indicate that quadratic Stark effect is most significant.

2. Experimental

The plasma device used in the present studies is a Mather type (1971) plasma focus which is capable of generating dense ($n_e \approx 10^{19}\,\mathrm{cm}^{-3}$) plasma and multi keV electron and ion temperatures in a 100ns time scale. This device is similar to the one which was studied in detail by Shyam (1981) and was developed as a neutron source for plasma diagnostics. It is essentially a pulsed Z-pinch device based on the principle of the pinch effect where the constriction (or pinching) occurs due to the interaction of high current ($\approx 10^4$ A) with its induced azimuthal self-magnetic field. The multielectrode configuration is known as squirrel cage type assembly having a cathode consisting of many bars instead of a cylinder as in Mather type (1971) around the central anode made of brass. The anode is 118 mm in length and 21 mm in diameter surrounded by twelve copper rods 180 mm long and 8 mm in diameter. The entire electrode assembly is housed in a glass vacuum chamber filled with hydrogen at about 5 mb pressure. A 2 kJ capacitor bank (10.2 μf, 20 kV) having an internal inductance of 40 nH is used for driving the plasma focus device. Schematic diagram of the plasma focus device used in the present studies is shown in figure 1.

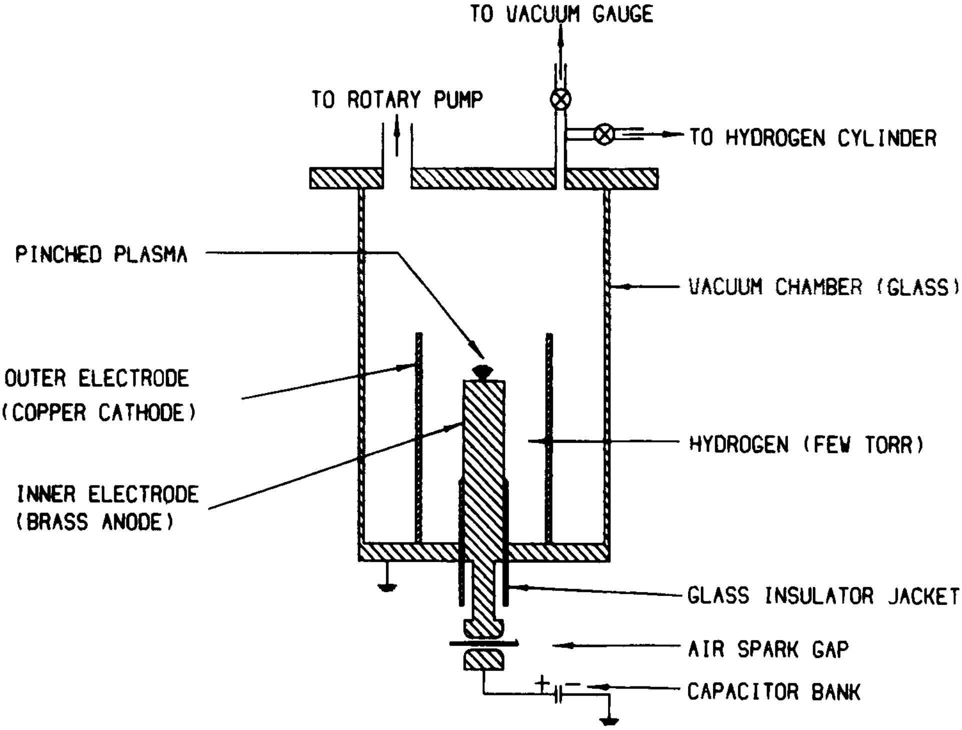

Figure 1. Schematic diagram of plasma focus device with squirrel cage electrode configuration.

The intense flash generated by the device was photographed on a one metre monochromator-cum-spectograph designed and fabricated in the Spectroscopy Division, BARC by Murty *et al* (1987). This instrument is equipped with a grating having 1200 grooves/mm and blazed at 1μ and yields a dispersion of 8 A/mm in the first order. Spectra were photographed in the wavelength region 4000–6000 Å using ORWO NP7 film.

A plasma focus discharge comprises of three phases (or regions). These are categorised as lift-off phase (near insulator), run-down phase (along anode) and pinch phase (off the end of the anode). Since the present investigations are aimed at studying the variation of the optical emissions in all the three phases, the emitted light from the plasma was photographed along the cathode to a height of 14 cm in an interval of 2 cm each using a fibre-optical light guide. In order to examine the shot to shot variation, spectra of three individual shots were recorded keeping the fibre bundle fixed at each slot.

3. Results and discussion

3.1 *Description of the observed spectral features*

Spectral emissions from the plasma focus were recorded in the region of 4000–6000 Å. Spectral features observed in 4500–5500 Å and 4000–4500 Å are shown in figures 2 and 3 respectively. Each figure consists of typically four spectra recorded from four

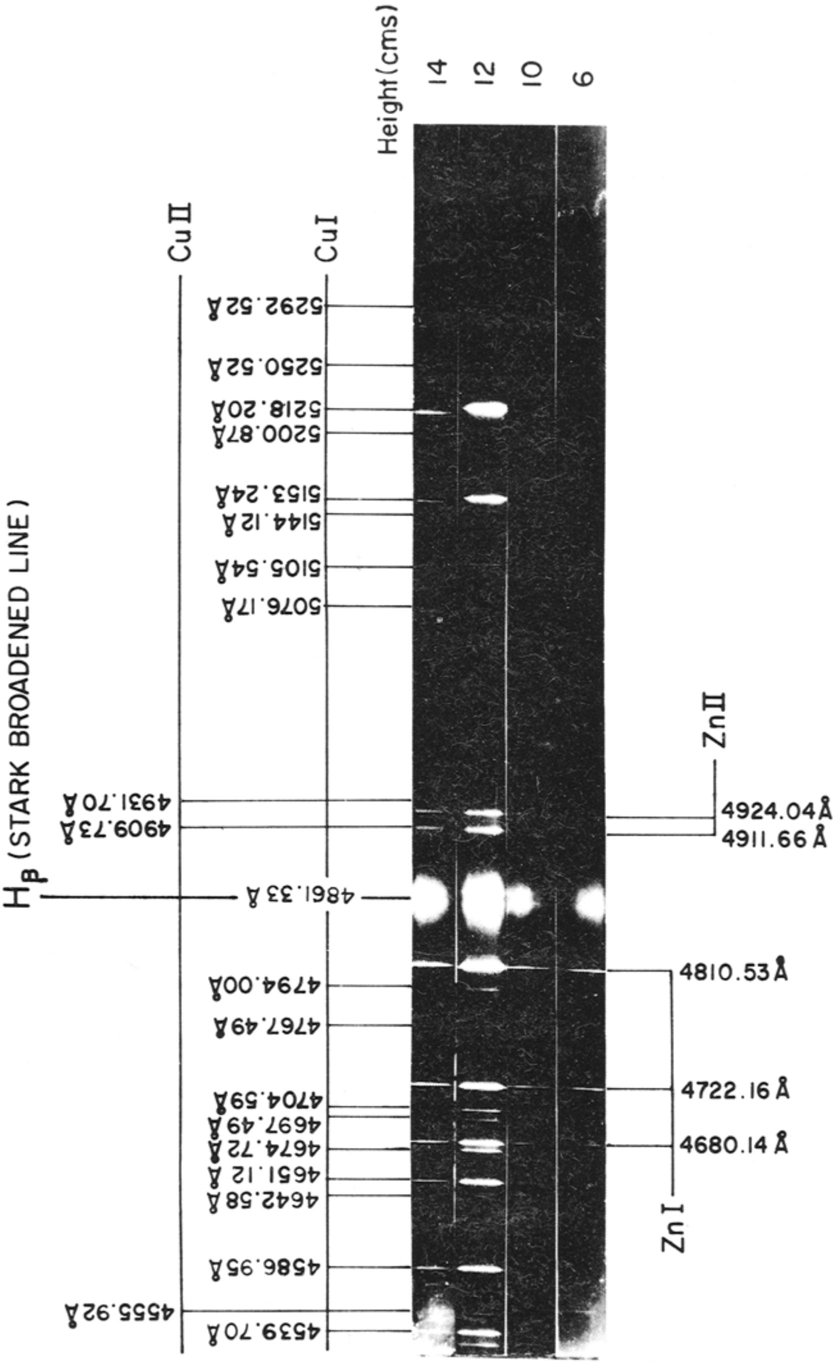

Figure 2. Emission spectrum (single shot) from plasma focus in 4500–5500 Å region at different heights from the base of the chamber.

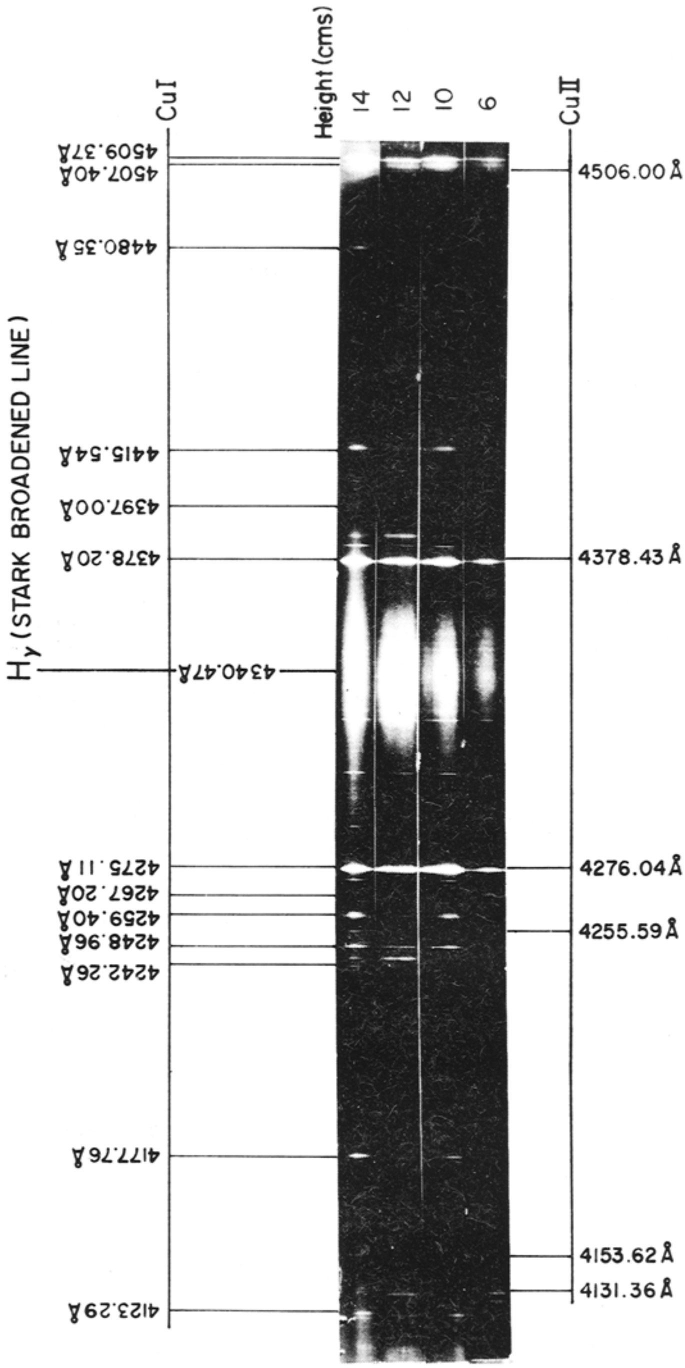

Figure 3. Emission spectrum (single shot) from plasma focus in 4000–4500 Å region at different heights from the base of the chamber.

slots located at heights 6, 10, 12 and 14 cm from the base of the vacuum chamber which represent the three phases of the plasma mentioned earlier where 12 cm slot corresponds to the focus region. Detailed identification of the lines observed showed that most of the lines were due to hydrogen and neutral and singly ionized copper and zinc atoms. All the spectral lines (particularly H_β and H_γ) showed significant broadening as can be seen from figures 2 and 3. Such a large broadening of the lines of hydrogen is due to linear Stark effect normally observed in the dense plasmas. Broadening observed in the neutral lines of Cu and Zn could be mainly due to quadratic Stark effect and perhaps to a small extent due to Doppler effect.

3.2 *Stark broadening of H_β and H_γ lines*

The theory of Stark broadening was first developed independently by Baranger (1958) and by Kolb and Griem (1958). Details of this theory can be found in text books by Sobel'man (1979) and by Griem (1974). When Stark broadening dominates the Doppler broadening, the line profiles do not depend critically on the electron and ion velocity distributions or the temperature. Hence electron density can be inferred from the line profiles without knowing plasma temperature precisely and without invoking the assumption of local thermodynamic equilibrium. Detailed calculation of the shape of neutral hydrogen emission lines as a function of plasma density and temperature is available in the text book by Griem (1974). The full width at half maximum (FWHM) for the Stark broadened hydrogenic emission lines is given by:

$$\Delta\lambda_{1/2} = 2{\cdot}5 \times 10^{-9} \alpha_{1/2} n_e^{2/3} \tag{1}$$

where $\Delta\lambda_{1/2}$ is the FWHM in Å, n_e is the electron density (cm^{-3}) and $\alpha_{1/2}$ is the shape factor. Values of $\alpha_{1/2}$ are available in the literature (Griem 1974). The factor $\alpha_{1/2}$ is weakly dependent on temperature. For example, for H_β line, in the temperature range of 5000–40000°K and 10^{14}–$10^{17}\,cm^{-3}$, the value of $\alpha_{1/2}$ changes by $\pm 20\%$ and it is taken as 0·08 (Scheeline *et al* 1984).

The densitometric traces of the H_β and H_γ lines (see figures 2 and 3) were taken, as per the procedures laid down by ASTM (1971), to obtain the Stark broadened profiles at four heights i.e. 6, 10, 12 and 14 cm from the base of the vacuum chamber used in the plasma focus device. Comparison of the H_β and H_γ profiles at the four heights show that the maximum value of FWHM is at a height 12 cm which is the pinch region of the plasma focus device employed in the present studies. Further the broadening of H_γ is larger than that of H_β since the Stark broadening is dependent on the principal quantum number, n (Griem 1974).

In order to establish that the observed broadening of hydrogen is mainly due to Stark effect, theoretical profiles obtained from the hydrogen Stark broadening tables (Vidal *et al* 1973) at electron densities of 10^{16} and $10^{17}\,cm^{-3}$ and temperatures of 5000 and 10000°K were superposed over the observed H_β profile as shown in figure 4. A comparison of the theoretical and experimental line profiles shows that the experimental line profile yielding an electron density of $5{\cdot}2 \times 10^{16}\,cm^{-3}$ lies in between the two theoretical profiles. The two bumps in the centre of H_β show up more strongly in the theoretical profiles than in the experimental one. Wiese and Kelleher (1971) attributed this discrepancy to not accounting for asymmetries or line shifts in the calculations.

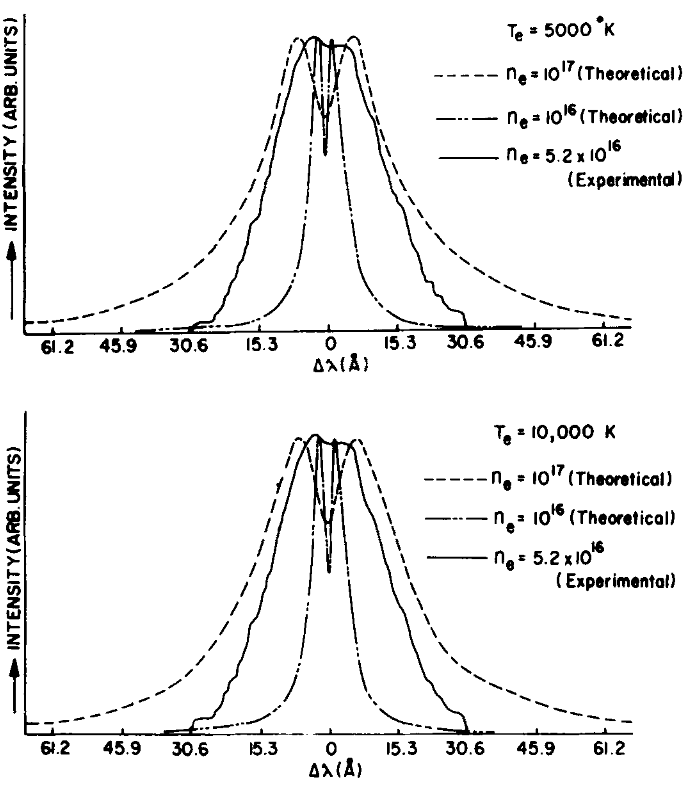

Figure 4. Comparison of theoretical and experimental profiles of H_β line.

Table 1. Variation of half widths of Stark broadened H_β and H_γ lines and the estimated electron densities.

Height (cm) from the chamber base	H_β(4861·33 Å)		H_γ(4340·47 Å)	
	$\Delta\lambda_{1/2}$(Å)	$n_e \times 10^{-16}$ (cm^{-3})	$\Delta\lambda_{1/2}$(Å)	$n_e \times 10^{-16}$ (cm^{-3})
6	26·	4·7	28	4·9
10	28	5·2	34	6·5
12	38	8·3	45	9·9
14	33	6·7	34	6·5

Making use of the $\Delta\lambda_{1/2}$ values of H_β and H_γ lines electron densities n_e, have been evaluated using (1). These values are listed in table 1. It is perhaps appropriate to mention here that the electron densities listed in table 1 are characteristic of the expanding plasma. This aspect is discussed in detail in one of the subsequent sections.

3.3 *Broadening of the lines of the electrode material*

The electrode material used was brass and hence most of the observed lines in the spectra (figures 2 and 3) were due to CuI, CuII, ZnI and ZnII because of electrode erosion and vapour emission. Further, these lines show large broadening.

Table 2. Variation of half widths ($\Delta\lambda_{1/2}$) of the electrode material (Cu and Zn) lines in plasma focus.

Wavelength (Å)	Emitter	$\Delta\lambda_{1/2}$(Å) 6*	10*	12*	14*
4177·76	CuI	1·0	1·5	1·5	1·0
4248·96	"	1·0	1·0	1·0	1·0
4259·40	"	2·0	2·0	2·5	2·0
4275·11	"	2·0	2·5	2·5	2·5
4415·54	"	2·0	2·5	2·5	2·0
4480·35	"	—	1·5	2·0	1·5
4586·95	"	—	3·0	3·5	2·0
4651·12	"	—	2·0	3·5	2·0
4680·14	ZnI	1·0	2·0	4·5	2·0
4722·16	"	1·0	2·5	4·5	2·5
4810·53	"	1·5	3·5	5·5	3·5
5105·54	CuI	—	1·5	2·5	1·0
5153·24	"	—	2·5	5·5	2·5

* Heights in cm from the base of the chamber.

In order to study the nature of broadening of these lines their densitometric traces were taken (ASTM 1971). The half widths, FWHM, were evaluated for several lines of CuI and ZnI at four zones corresponding to heights 6, 10, 12 and 14 cm from the base of the chamber. These are presented in table 2. A detailed examination of table 2 shows that the width varies at different heights from the base of the chamber, with maximum at the focus region (12 cm height).

3.3.1 *Doppler effect.* The broadening of the spectral lines in emission sources is due to Doppler (temperature) effect, Stark (collision) effect and instrumental width. In addition to these factors some of the CuI lines exhibit diffuseness due to autoionization effect (Allen 1932). Doppler effects are either due to thermal effect or the directed motion of the emitting atoms or ions. If the line broadening is due to Doppler effect, the emitting atoms have a Maxwellian velocity distribution, the broadened line profiles will have a Gaussian shape. The Doppler width of a spectral line is given by the expression (Kastner 1980):

$$\Delta\lambda_{1/2} = (7{\cdot}162 \times 10^{-7})\lambda T^{1/2}\,\mathrm{M}^{-1/2} \tag{2}$$

where wavelength units are in Angströms, temperature is in degrees Kelvin and mass of the atom M in atomic mass units.

On the contrary if the line broadening is due to unresolved macroscopic motion which may also result in Gaussian profile whose half width is governed by the expression:

$$\Delta\lambda_{1/2} = [\langle v_r/c\rangle^2_{\mathrm{av}} \ln 2]^{1/2}\lambda_0 \tag{3}$$

where v_r is the relative macroscopic velocity which has nothing to do with the kinetic temperature referred to in (2). The observed line widths if attributed totally to Doppler effect yield temperatures of the order of a few hundred electron volts or velocities of the order of 10^7 cm/s. In either case it is difficult to visualise the existance of neutral and singly ionised species of copper and zinc. At such high temperatures we expect the atoms to exist mainly in highly ionised states. The time variation of intensities of various spectral lines was carried out by making a mask with slits at positions where the unblended intense lines (e.g. 4810·53 Å of ZnI, 4861·33 Å of H_β and 5153·24 Å of CuI) fall in the focal curve of the spectrograph (Rout *et al* 1987). Light signals from the slits were transmitted through a long fibre optic light guide to the photomultiplier tube kept nearer to an oscilloscope to maximise the signal to noise ratio. From these investigations it was concluded that the peak intensity emission of H_β occurs at 50 μs after the focus formation whereas the peak intensity emission of CuI and ZnI occurs 25 μs after focus formation.

3.3.2 *Instrumental and inherent line broadening.* Before making any valid conclusions about broadening of spectral lines from the plasma focus source, it is very important to ascertain the contribution to line width from instrumental broadening and inherent width of energy levels (which is significant in the case of the diffuse series copper). These factors were evaluated from the spectrum of Cu-Ne hollow cathode operated at 15 mA and a 3 A DC are source, by adopting standard spectroscopic techniques (Brode 1952). Line widths thus obtained are compared with those of plasma focus listed in table 3, from which it can be seen that the instrumental width is 0·6 Å. The half widths of all the spectral lines observed in plasma focus source (including lines belonging to the diffuse series of CuI) are significantly larger.

3.3.3 *Broadening due to quadratic Stark effect.* It is clear from the foregoing discussions that the broadening of the lines of the electrode material observed in the plasma focus is definitely more than the contributions from Doppler, instrumental and natural line widths. Stark broadening of spectral lines caused by the interaction of atoms with surrounding particles depends on the concentration of perturbing particles. Calculation of the contour of a spectral line with all the possible interactions taken into account is an extremely complex task. General theory of the Stark broadening of the spectral lines based on binary approximation model is found in greater detail in the text book by Sobel'man (1972). According to this theory interactions with the nearest perturbing particle (binary interactions) play the principal role in line broadening, therefore triple and multiparticle interactions can be neglected. The perturbation is adiabatic hence it does not cause transitions between different states of atoms. While the broadening due to electrons moving with velocities faster than ions in a plasma is calculated on the basis of "impact approximation", the perturbation between the slowly moving ions and the radiator (which in the present case is the atom emitting the spectrum) is known as 'quasi-static broadening' or 'ion bradening'. According to this theory a perturbing particle at a distance R from the atom leads to frequency shift $\Delta\nu$ given by

$$\Delta\nu = C_n/R_n \tag{4}$$

where n is a whole number and C_n is a constant. When $n = 2$ the splitting of levels leads to "linear Stark effect" which holds good for the broadening of lines of hydrogen and hydrogenic ions. When $n=4$, the frequency shift given by $\Delta\nu = C_4 R^{-4}$ leads to quadratic Stark effect which holds good for non-hydrogenic atoms. The constant $C_4(\text{cm}^4\,\text{s}^{-1})$ is called the Stark coefficient for quadratic Stark effect. In the frame work of the Lindholm impact theory (Sobel'man 1972) the width of a spectral line broadened due to quadratic Stark effect is given by:

$$\Delta\lambda_{1/2}(\text{Å}) = 11{\cdot}4C_4^{2/3}v^{1/3}n_e\lambda^2/2\pi c \tag{5}$$

where v is the mean velocity of electron, n_e is electron density, λ is the wavelength of the spectral line and c, the velocity of light.

Since CuI, CuII, ZnI and ZnII belong to non-hydrogenic species, the theoretical considerations lead us to believe that the broadening of these spectral lines is due to quadratic Stark effect (see table 3). A careful examination of the profiles exhibit contour asymmetry which is characteristic of quadratic Stark effect (Sobel'man 1972).

In order to evaluate the contribution of quadratic Stark effect to the observed broadening it is necessary to consider the contributions due to other broadenings i.e. due to Doppler effect, the instrumental and natural line widths. The line profiles due to Doppler and instrumental are Gaussian whereas profiles of Stark and natural line broadening are Lorentzian. For the case in which there are two or more competing mechanisms such as instrumental ($\Delta\lambda_{1/2}^{\text{inst}}$) and Doppler ($\Delta\lambda_{1/2}^{\text{Doppler}}$) broadening represented by a Gaussian function, their deconvolution is attained by adding their half widths in the following way:

$$(\Delta\lambda_{1/2}^{\text{total}}) = [(\Delta\lambda_{1/2}^{\text{inst}})^2 + (\Delta\lambda_{1/2}^{\text{Doppler}})^2]^{1/2} \tag{6}$$

where $\Delta\lambda_{1/2}^{\text{total}}$ is the total Gaussian width. On the other hand, two Lorentzian half widths due to Stark and natural broadening add linearly i.e.

$$\Delta\lambda_{1/2}^{\text{total}} = \Delta\lambda_{1/2}^{\text{Stark}} + \Delta\lambda_{1/2}^{\text{natural}} \tag{7}$$

Table 3. Comparison of line broadening of Cu and Zn lines in DC arc, hollow cathode and plasma focus.

Wavelength (Å)	Emitter	Transition	$\Delta\lambda_{1/2}$(Å) (FWHM) DC arc	Hollow cathode	Plasma focus
4248·96	CuI(S)	$4p'\,^4P^0_{1/2} - 5s'\,^4D_{1/2}$	0·6	—	1·0
4275·11	CuI(S)	$4p'\,^4P^0_{5/2} - 5s'\,^4D_{7/2}$	0·9	0·6	2·5
4480·35	CuI	$4p\,^2P^0_{1/2} - 6s\,^2S_{1/2}$	0·8	—	2·0
4586·95	CuI(D)	$4p'\,^4F^0_{7/2} - 5s'\,^4D_{5/2}$	1·2	—	3·5
4651·12	CuI(S)	$4p'\,^4F^0_{9/2} - 5s'\,^4D_{7/2}$	0·7	0·6	3·5
4680·14	ZnI	$4p\,^3P^0_0 - 5s\,^3S_1$	0·7	—	4·5
4722·16	ZnI	$4p\,^3p^0_1 - 5s\,^3S_1$	1·0	—	4·5
4810·53	ZnI	$4p\,^3P^0_2 - 5s\,^3S_1$	1·0	—	5·5
5105·54	CuI	$4s^2\,^2D_{5/2} - 4p\,^2P^0_{3/2}$	0·6	0·7	2·5
5153·24	CuI	$4p\,^2p^0_{1/2} - 4d\,^2D_{3/2}$	0·8	0·6	5·5
5218·20*	CuI	$4p\,^2P^0_{3/2} - 4d\,^2D_{5/2}$	1·0	0·4	7·5
5292·52	CuI(S)	$4p'\,^4D^0_{7/2} - 5s'\,^4D_{7/2}$	0·6	0·5	2·0
5700·24	CuI	$4s^2\,^2D_{3/2} - 4p\,^2P^0_{3/2}$	0·8	0·6	2·0
5782·13	CuI	$4s^2\,^2D_{3/2} - 4p\,^2P^0_{1/2}$	0·7	0·6	2·5

* Blended line.

S and *D* in brackets in column 2 indicate sharp and diffuse line respectively.

If the profiles of a line due to two different broadening mechanisms are $I_1(\Delta\lambda)$ and $I_2(\Delta\lambda)$ then the resultant profile is obtained by a convolution integral

$$I_{\text{mean}}(\Delta\lambda) = \int_{-\infty}^{+\infty} I_1(\Delta\lambda - \Delta\lambda')I_2(\Delta\lambda')\mathrm{d}(\mathrm{d}\lambda'). \tag{8}$$

The deconvolution procedure is described in greater detail by Konjevic and Roberts (1976) which is adopted in the present studies to evaluate the half width due to the quadratic Stark effect. The widths thus obtained have been used to calculate the quadratic Stark coefficients C_4 for the lines of Cu and Zn, making use of (5). The value of electron density (n_e) used correspond to the focus region, the mean electron velocity is calculated from the expression:

$$v = (\pi kT/2m)^{1/2} \tag{9}$$

where k is Boltzman constant, m is the electron mass and T is the temperature. These values of C_4 obtained for $v = 4{\cdot}88 \times 10^7$ cm/s and $n_e = 8{\cdot}3 \times 10^{16}\,\text{cm}^{-3}$ are included in table 4. It can be seen from this table that the value of C_4 varies from to 10^{-14} to $10^{-12}\,\text{cm}^4/\text{s}$ which is expected for quadratic Stark effect (Sobel'man 1972).

3.4 *Temperature measurement from line intensity ratios*

Since no anamolies were observed in the intensity distribution of CuI spectrum LTE conditions were presumed and the plasma temperature has been evaluated making use of the line intensity ratio method described in detail by Boumans (1966). Three pairs of lines belonging to neutral Copper atom were chosen to evaluate the excitation temperature T using the expression:

$$T = \frac{5040(V_a - V_b)}{\log[(gA)_a/(gA)_b] - (\log \lambda_a/\lambda_b) - \log(I_a/I_b)} \tag{10}$$

Table 4. Quadratic Stark coefficient C_4 evaluated for the lines of CuI and ZnI lines.

Wavelength (Å)	Emitter	$\Delta\lambda_{1/2}$(Å) (Obs)	$\Delta\lambda_{1/2}$(Å) (Lorentzian)	$C_4 \times 10^{13}$ (cm^4/s)
4248·96	CuI	1·0	0·62	0·8
4275·11	"	2·5	2·35	5·8
4480·35	"	2·0	1·81	3·4
4586·95	"	3·5	3·37	8·1
4651·12	"	3·5	3·37	7·8
4680·14	ZnI	4·5	4·43	11·4
4722·16	"	4·5	4·43	11·2
4810·53	"	5·5	5·43	14·4
5105·54	CuI	2·5	2·35	8·4
5153·24	"	5·5	5·43	11·7
*5218·20	"	7·5	7·44	18·0
5292·52	"	2·0	1·81	2·1
5700·24	"	2·0	1·81	1·7
5782·13	"	2·5	2·35	2·3

* Indicates blended line.

Table 5. Evaluation of excitation temperature from line intensity ratios of Cu lines.

	Temperature (°K)	
Linepair	Cu arc	Plasma focus
5218/5106	7700	9700
5153/5106	8800	9800
5218/5782	7300	7500

where V is the excitation potential in eV, A the transition probability, g the statistical weight factor λ the wavelength and the a and b subscripts refer to the two lines respectively. The values thus obtained are listed in table 5. The temperature evaluated for different sources like low current DC arc are also listed for comparison. It is important to mention here that the temperatures evaluated from this method do not represent the plasma temperature in the focus region. However these values signify that the environment in which the copper and zinc atoms emit radiation is relatively cooler zone of the plasma where the temperature and the electron densities are lower compared to those in the focus region.

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