FIZIKA, 2 (1970) 121-128

LASER INTERFEROMETRIC MEASUREMENTS OF ELECTRON DENSITY IN A SHOCK WAVE PLASMA*

N. KONJEVIĆ, Lj. ĆIRKOVIĆ and J. LABAT

Institute of Physics, Beograd

Received 31 December 1969; revised manuscript received 3 February 1970

Abstract: The application of a laser interferometric technique is described for the investigation of electron density behind the reflected shock wave in an electromagnetic, T type shock tube. The tube was filled with the mixture of argon and hydrogen (9 : 1) to the pressure of 1 Torr. The advantages and limitations of the method are discussed. The electron density in plasma ($2.11 - 3.57 \cdot 10^{17}$ cm^{-3}) was determined simultaneously by the laser interferometry at two different wavelengths and by the measurements of the Stark broadening parameters of H_β line. Results of these two sets of measurements agree within 4 %.

1. Introduction

Laser interferometers have been widely used for measurements of time varying electron concentration in plasmas[1, 2, 3, 4],** due to some advantages over other diagnostic methods. They can be used to measure transient electron densities from 10^{13} to 10^{16} cm^{-3} what is in the range between the microwave and optical interferometric techniques. If plasma is placed within the laser cavity electron density region of $10^{11} - 10^{14}$ cm^{-3} can be reached[2, 5, 6]. Further the spatial resolution of the interferometer, when plasma is placed within the laser cavity is excelent in comparison with microwave diagnostic methods.

2. Interferometric method

The first laser interferometer was constructed by Ashby *et al*[7, 8] and the principle of operation is shown in Fig. 1. It consists of a He-Ne laser with

---

* This work was partially supported by Federal Fund for Scientific Work

** Since there is a great number of papers which deal with laser interferometry, only a few review papers are given where further references can be found.

an external plane mirror M_3 which forms a Fabry-Pèrot etalon with laser mirror M_2. The external cavity contains the plasma whose index of refraction is to be measured. In our case it was a shock wave produced plasma. Change of phase in external reflected beam at mirror M_2 due to variations of the refractive index in the external cavity, controls the feedback to the laser and hence its output. The interference fringes in external cavity can be detected in two ways:

1) intensity of the laser itself can be used to observe the fringes (detector D_2),

2) inserting the glass slide in the external cavity (Fig. 1) the part of the interfering beam is reflected onto another detector D_1. In the first case laser acts in the same time as the source and detector, but in both cases laser interferometer measures only a change in plasma refractive index and does not indicate the steady state conditions.

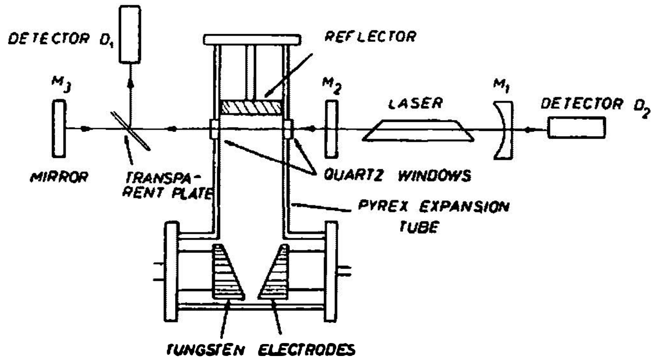


Fig. 1. Shematic diagram of the laser interferometer and »T« tube.

The advantage of detection of fringes in the external cavity is practically unlimited time response[9]. Alternatively if the laser is used as a detector, the signal is amplified and this simplifies the measurements, but the time response is worse. Which method will be employed depends upon the rate of change of plasma refractive index.

It should be mentioned that if a laser is used as a detector at few different wavelengths, time response varies also from line to line. For example, at a low gain transition such as the 6328 Å He-Ne laser line, the typical time response does not exceed a few microseconds, but for 3.39 μ line it is as high as 0.2 μs. More details about time response of the laser interferometer can be found elsewhere[4, 10].

3. *Plasma refractivity*

Since the laser interferometer detects only the variations of plasma refractive index, the peak electron concentration in the shock wave plasma has to be determined during the transient conditions while the plasma is being fully established or alternatively following decay. During these changes interferometric fringes arise due to the alteration in concentration of all components: neutrals, ions, electrons etc. and this makes measurements of electron concentration very difficult. However, following Alpher and White[11], one can take advantage of the large dispersion of the electron component and determine the electron concentration from the number of fringes obtained at two different wavelengths. Thus:

$$\mu(\lambda_1) - \mu(\lambda_2) \sim \mu_e(\lambda_1) - \mu_e(\lambda_2) = -4.49 \cdot 10^{-14} (\lambda_1^2 - \lambda_2^2) N_e , \qquad (1)$$

where $\mu(\lambda)$ is the refractive index at particular wavelength, and N_e is the electron concentration per cm^3.

When the contribution of other plasma species to the plasma refractive index can be neglected it is possible to determine electron density using single wavelength interferometry:

$$\mu(\lambda) \sim \mu_e(\lambda) = -4.49 \cdot 10^{-14} \lambda^2 N_e . \qquad (2)$$

This is fair approximation in our case even for the shorter wavelength used (6328 Å), since the electron densities were of the order of few times 10^{17} cm^{-3}.

However, there is another reason to employ two wavelengths interferometry. When working with Mach-Zehnder interferometer at a single wavelength (5330 Å or 4545 Å) in a T tube hydrogen plasma McLean and Ramsden[12] have found electron densities by 10 — 15 % too low. This was taken to indicate the presence of the boundary layer of cold, high density neutral gas near the wall of the tube.

Therefore special care was taken to investigate boundary layer wich may introduce the error in determination of electron density due to:

- uncertainty of plasma length, and
- smaller change of refractive index resulting in lower electron concentration (neutral gas has refractive index with positive sign).

The latter effect is inversely proportional to the square of the wavelength of light employed for interferometry.

The number of fringes f produced by plasma length L due to a change of refractive index $\Delta\mu$ at wavelength λ is given by:

$$f = \frac{\Delta\mu\, 2L}{\lambda}\,. \tag{3}$$

The factor two arises because the laser beam traverses the plasma length L twice. Hence, for two different wavelengths

$$\frac{1}{2L}\,(\lambda_1 f_1 - \lambda_2 f_2) = -\,4.49\cdot 10^{-14}\,(\lambda_1^2 - \lambda_2^2)\,N_e\,, \tag{4}$$

or for the single wavelength:

$$\frac{\lambda f}{2L} = -\,4.49\cdot 10^{-14}\,\lambda^2 N_e\,, \tag{5}$$

where both λ and L are in cm. Therefore to increase the sensitivity of the interferometer the plasma length was increased (tube radius is larger than usual for T tubes). This also decreases the percentage error introduced by the boundary layer. Special care should be taken to insure that reflected shock wave plasma is homogenous under these conditions.

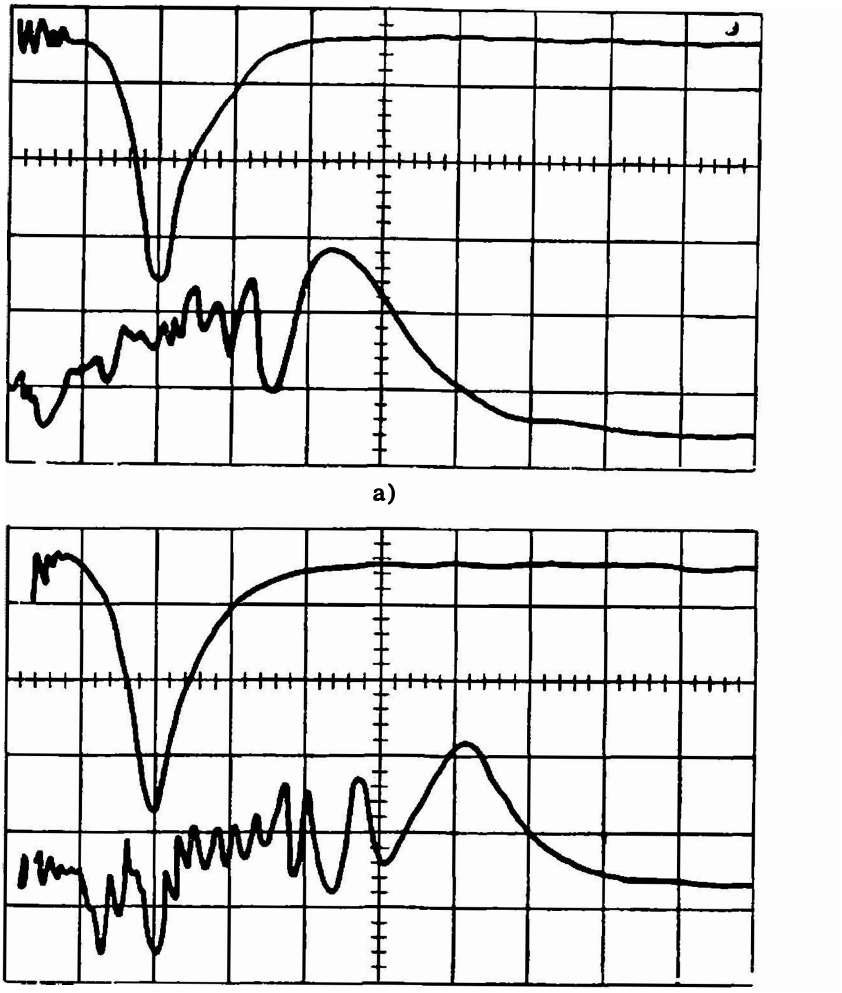
4. Experimental apparatus and procedure

Details about experimental apparatus can be found elsewhere[13, 14]. Shematic diagram of the plasma source — an electromagnetically driven T tube, is given in Fig. 1. The discharge was driven by 7.5 μF condensor bank charged to voltages from 14 to 19 kV. During the experiment a continous flow of argon — hydrogen mixture (9 : 1) of 0.1 lit/min has been sustained at a pressure of 1 Torr. All observations of plasma were taken 12 mm from the reflector which was placed at a distance 12.5 cm from electrodes, at the moment of maximum density.

The profile of H_β line was photoelectrically recorded using SPM-2 Zeiss grating monochromator (inverse linear dispersion 40 Å/mm), and the photomultiplier RCA 1P28. During the line scanning great care was taken to insure linearity in photomultiplier operation. Experimentally obtained profiles were compared with theoretical profiles by Griem, Kolb and Shen[15, 16] and also by Kepple and Griem[17], using a standard fitting procedure[18].

For the measurements of electron density a small commercial He-Ne laser capable to operate at two different wavelengths 6328 Å and 1.15 μ, was used.

The modulation of the laser intensity in infrared at 1.15 μ was followed using photomultiplier with S_1 photocathode. Interference fringes at 6328 Å were detected in external cavity by means of photomultiplier. Interference fringes were displayed on a double beam oscilloscope together with continuum radiation monitored at the same part of a plasma by means of monochromator and photomultiplier. Characteristic fringes obtained at two different wavelengths at condensor bank voltage of 16 kV are given in Fig. 2. Since the maximum electron density was measured the peak of the continuum radiation indicated the point at which the electron concentration reaches



a)

b)

Fig. 2. Interference fringes and continuum radiation (upper trace) versus time at a) 6328 Å and b) 1.15 μ. Time base 10 μs/cm.

maximum and began to decay. This is very usefull because it is sometimes difficult to decide when electron density stops to increase and began to decrease.

The homogenity of distribution of electron density in the T tube is important since the laser interferometer measures an average electron concentration along the interferometric beam. Thus the plasma homogenity was extensively studied using STL image convertor camera in streak and framing mode, and also by measuring the electron density from Stark broadening of H_β taken at various positions along the shock tube radius. Both methods firmely proved that a homogenous distribution of electron density across the T tube existed.

5. *Experimental results and discussion*

Measured electron densities are given in the Table. All results obtained from laser interferometry represent an average value of at least ten measurements. The main inaccuracy in electron density measurements was introduced by the uncertainty of plasma length. The thickness of boundary layer at the tube walls is estimated to be less than 1 mm, and the accuracy with which the fringe shifts can be measured is estimated to be ± 1/10 of fringe. Thus the experimental error in a single wavelength electron density measurements did not exceed ± 6 %.

Table

Comparison of electron density values using spectroscopic and interferometric methods.

Temperature °K	Interferometric data $N_e \cdot 10^{-17}$ cm^{-3}				H_β profile $N_e \cdot 10^{-17}$ cm^{-3}	
	6328 Å	1.15 μ	Two wavelength	average	Griem et al[16]	Kepple, Griem[17]
9400	2.06	2.12	2.15	2.11	2.01	2.19
10200	2.64	2.76	2.83	2.74	2.64	2.82
14500	3.58	3.56	3.56	3.57	3.44	3.51

From the values given in the Table one can conclude good agreement between electron density measurements at different wavelengths, what indicates that there is no detectable boundary layer of neutral gas near the walls of the shock tube in argon. Thus interferometric measurement at one single wavelength is quite sufficient. For greater sensitivity the longest possible wavelength should be used[19, 20]. This is limited by choice of laser source, infra red detector and also by the plasma cut-off frequency. The disadvantage of the infra red wavelength is in the difficulty of optical alignment.

Further remarkable agreement between interferometric and spectroscopic measurements in the range 2.11 — $3.57 \cdot 10^{17}$ cm^{-3} is evident, specially when the recent corrected theory of H_β broadening by Kepple and Griem[17] is used. Corrections introduced by this theory involve reduction of line broadening parameter $\alpha_{1/2} = \Delta\lambda_{1/2}/F_0$ (the half-half width of the line in the units of normal field strength), for temperatures below $1.5 \cdot 10^4$ °K. This will cause the increase of electron density values for 2 — 9 % in the range of temperatures that were measured in this experiment. It should be noticed that the temperature was measured from the relative intensities of A II lines as described elsewhere[14]. Also, it should be underlined that our measurements were performed in the mixture of argon and hydrogen (9 : 1) what can make some difference for electron density measurements from Stark broadening of H_β due to the superposition of some argon lines on the wings of H_β .

Finally as a conclusion of this paper one can say that the laser interferometry proved to be an excellent diagnostic tool. Although it does not give the whole picture of the plasma like e. g. Mach-Zehnder interferometer, it simplifies the measurements of electron density and easily increases the accuracy by employing longer wavelengths. This would be much more difficult technically with the classical interferometric techniques.

Reference

1) J. B. Gerardo and J. T. Verdeyen, Proc. IEEE **52** (1964) 690;
2) J. T. Verdeyen and J. B. Gerardo, A.G.A.R.D. Fundamental Studies of Ions and Plasmas, Pisa 1965;
3) F. Rostas, J. de Physique, **27** (1966) 367;
4) N. Konjević, H. Edels and K. R. Hearne, Summer school on Physics of Ionized Gases, Herceg Novi, 1968, edited by B. Perović, Beograd 1969;
5) W. B. Johnson, A. B. Larsen and T. P. Sosnowski, Proc. 7th Int. Conf. Ioniz. Phenomena in Gases, Beograd, 1965;
6) J. T. Verdeyen, B. E. Cherrington and M. E. Fein, Appl. Phys. Lett. **9** (1966) 360;
7) D. E. T. F. Ashby and D. F. Jephcott, Appl. Phys. Lett. **3** (1963) 13;
8) D. E. T. F. Ashby, D. F. Jephcott, A. Malein and F. A. Raynor, J. Appl. Phys. **36** (1965) 29;
9) J. B. Gerardo, J. T. Verdeyen and M. A. Gusinow, J. Appl. Phys. **36** (1965) 2146;
10) E. B. Hooper Jr. and G. Bekefi, J. Appl. Phys. **37** (1966) 4083;
11) R. A. Alpher and D. R. White, Phys. Fluids **2** (1959) 162;
12) E. A. McLean and S. A. Ramsden, Phys. Rev. **140** (1965) A 1122;
13) N. Konjević, J. Labat, Lj. Ćirković and J. Purić, Proc. 9th Int. Conf. on Phenomena in Ionized Gases, Bucharest, 1969;

14) N. Konjević, J. Labat, Lj. Ćirković and J. Purić, Z. Phys. **235** (1970) 35;
15) H. R. Griem, A. C. Kolb and K. Y. Shen, Astrophys. J. **116** (1959) 4;
16) H. R. Griem, A. C. Kolb and K. Y. Shen, Astrophys. J. **135** (1962) 272;
17) P. Kepple and H. R. Griem, Phys. Rev. **173** (1968) 317;
18) J. Labat, Ph. D. Thesis, University of Liverpool, (1963) (unpubl.);
19) J. Maignan, E. Fabre and P. Vasseur, Phys. Lett. **26A** (1968) 135;
20) N. Konjević and K. R. Hearne, Phys. Lett. **28A** (1968) 309.

MERENJE ELEKTRONSKE GUSTINE U PLAZMI UDARNOG TALASA POMOĆU LASERSKE INTERFEROMETRIJE

N. KONJEVIĆ, Lj. ĆIRKOVIĆ i J. LABAT

Institut za fiziku, Beograd

Sadržaj

U radu je opisana primena laserske interferometrijske tehnike za merenje elektronske gustine u plazmi iza reflektovanog udarnog talasa. Plazma je proizvedena u elektromagnetnoj T cevi napunjenoj smesom argona i vodonika (9 : 1) na pritisku od 1 tora. Prednosti i ograničenja metode su detaljno diskutovane. Elektronska gustina plazme (2.11 — 3.57 · 10^{17} cm^{-3}) određena je simultano laserskom interferometrijom na dve talasne dužine i iz merenja Štarkovog širenja vodonikove H_β linije.

Vrednosti elektronske koncentracije izmerene laserskom interferometrijom odnosno koristeći profil H_β linije i raniju teoriju Griem-a[16] razlikuju se za više od 5 % kod svih vrednosti temperature (vidi Tabelu). Korekcije koje su unete u najnovijoj teoriji širenja H_β linije u radu Kepple-a i Griem-a[17] daju veće vrednosti elektronske koncentracije tako da je slaganje sa interferometrijskim merenjima bolje od 4 %.