Electron Density Determination in an Arc Plasma by Laser Interferometry

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(Z. Naturforsch. **30 a**, 1560–1562 [1975]; received September 5, 1975)

By means of a 2 λ-Michelson-Interferometer the electron density has been determined with a mean accuracy of 2% in the axis of a wall-stabilized arc which has been operated in Argon at atmospheric pressure in a range from 10 to 100 A. The measurements have been performed with He-Ne-lasers at wavelengths $\lambda_1 = 0.63\ \mu$ and $\lambda_2 = 1.15\ \mu$.

1. Introduction

In collison dominated plasmas the electron density is the most important parameter. Therefore laser interferometry is very attractive because it allows a direct determination of this quantity without any rigid assumptions such as, e.g., local thermodynamical equilibrium (LTE). For references see, e.g., Griem [1], Alpher and White [2] or Kunze [3].

In the experiment described in this paper we intended to test how accurate the electron density can be measured in a well-defined plasma by means of an appropriate interferometer. We have chosen a wallstabilized arc and a Michelson interferometer.

By switching off the arc current the change of refractivity in the arc axis can be measured, whereas the special arrangement of the interferometer allows simultaneous fringe detection at two different wavelengths. That should be an improvement to the arrangement described in the very extensive paper of Hearn and Konjevic [4], who have measured the electron density in the axis of an arc column by means of a "coupled cavity" interferometer, whereas the two fringe measurements could be performed only time sequentially with a loss in accuracy.

Baum et al. [5] carried out side-on observations of the arc column with a two wavelength interferometer utilizing the radial symmetry for Abel inversion. Because of the differentially thin homogeneous layers and the errors introduced by the inversion procedure – especially in the vicinity of the axis – the accuracy of the electron density determination is only 10 to 15%. For this reason we observed the arc end-on as described by Hearn and Konjevic. End-on observation, however, is affected by the plasma inhomogeneities in the electrode regions, thus leaving a possible uncertainty of the plasma length. For a high precision electron density determination the influence of those cold layers on the effective plasma length must be investigated.

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2. The Wall-stabilized Arc

The arc is schematically shown in Figure 1. It consists of 33 water cooled copper plates, 3 mm thick, with a central bore of 4 mm. The plates are electrically insulated by 0.1 mm thick Pertinax. The arc length is limited to 104 mm by a ring anode and four tapered cathodes, all made of tungsten. The arc was closed up by optical flat Quartz windows. The arc has been operated in Argon at atmospheric pressure and at currents between 10 and 100 A supplied by a dc-generator, 480 V/120 A. The residual ripple of the current was no more than 0.5%. The reproducibility and the stability of the arc has been tested from separate spectroscopic and interferometric investigations. The change in plasma refractivity was achieved by switching off the arc by means of a Thyristor and a capacitor bank of 4 mF. The cut-off time was about 2 μsec. The capacity was chosen large enough to avoid a notable recovery of the arc voltage during the measuring time of 100 – 300 μsec.

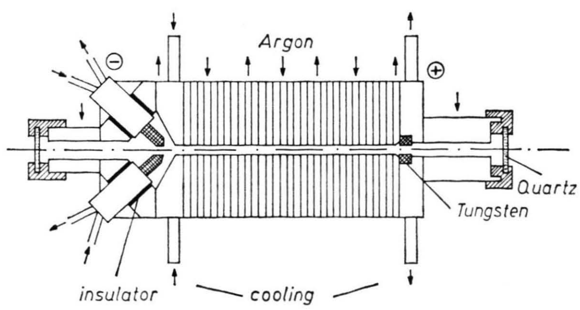

Fig. 1. Scheme of the wall-stabilized arc.

3. The Optical Interferometer

The interferometer used in this experiment is schematically shown in Figure 2. A more detailed description has been given by Teuber and Weiss [6]. The set-up consists of two Michelson interferometers with combined measuring and reference arms. Because of the radial inhomogeneity of the arc plasma the measuring beams have to be thread very accurately and sufficiently focussed through the arc axis. The beam waists of the He-Ne-lasers therefore are imaged by lenses of appropriate focal lengths into the middle of the arc thereby reducing the waist diameters from 0.65 mm (1.2 mm) to 0.24 mm for both wavelengths. At the ends of the plasma column the beam diameters are 0.29 mm and 0.39 mm respectively. The term diameter means that the lateral intensity of the Gaussian laser beam has dropped down to e^{-2}.

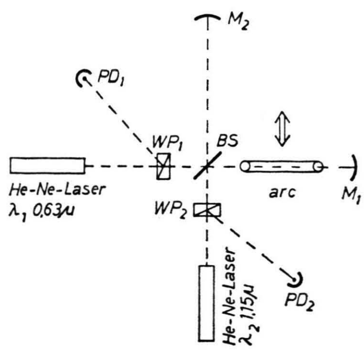

Fig. 2. The optical interferometer with beam splitter BS, spherical mirrors M, Wollaston prisms WP and photodiodes PD.

The two beams are separated by wavelength selective mirrors and reflected by spherical mirrors M arranged in such a manner that their curvatures coincide with those of the incoming wavefronts.

The returning beams are coupled out by means of Wollaston prisms WP, whereby a feedback into the laser cavities is avoided.

For a detection of the interference signals at wavelength λ_1 and λ_2 respectively interference filters block out most of the unwanted plasma light. The transmitted laser light is focussed onto a photodiode PD.

The sinusoidal interference signals are amplified and displayed onto an oscilloscope. A typical record is shown in Figure 3. In order to obtain undistorted signals of this kind the interferometer has to be decoupled from mechanical vibrations, and the arc has to be decoupled from the interferometer. Moreover, the fluctuations of the arc current should be negligible (in the present experiment $\leq 1/2\%$). The example shown in Fig. 3 demonstrates the satisfactory performance of this interferometric arrangement.

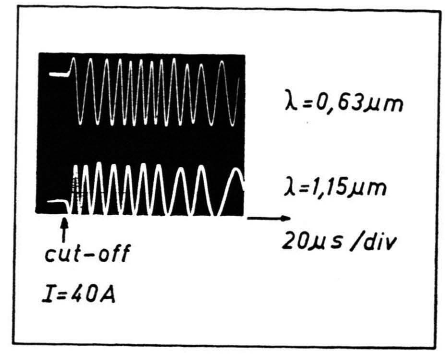

Fig. 3. Record of a set of interferograms.

4. Discussion of the Results

For the determination of the change of electron density after switching off the arc current the transient fringe shifts for both wavelengths have to be evaluated from interferograms as shown in Figure 3.

We have applied standard formulas [2, 4] in order to derive electron densities from fringe shift measurements. The ratio of polarisabilities of neutral Argon at wavelengths λ_1 and λ_2 has been taken to 1.01. The contributions of highly excited states to the refractive index has been estimated to less than 1% and has been neglected at all [1, 5].

A typical result of a complete evaluation is shown in Figure 4. The modulus of the change of electron density $|\delta N_e|$ is plotted versus time. Before cut-off $|\delta N_e|$ is zero. As the number of electrons decreases due to recombination, $|\delta N_e|$ is attaining a constant

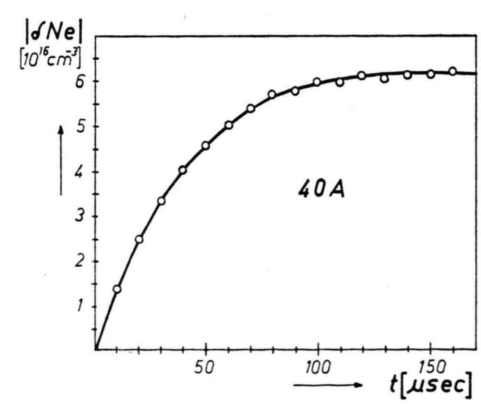

Fig. 4. The change of electron density with time evaluated from the record in Figure 2.

value which is identical with the electron density of the stationary arc before cut-off.

Figure 5 shows a plot of the electron density versus arc current for the range 10 to 100 A. Each point in the plot is the mean value from up to ten

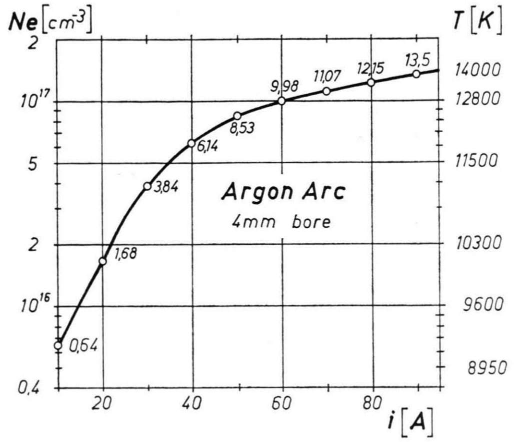

Fig. 5. The electron density as function of arc current. The temperature scale at right hand side is related to N_e (LTE). The figures at the experimental data points are the electron density results in units of 10^{16} cm^{-3}.

single interferograms. The mean deviation is less than 2% for arc currents higher than 20 A. For the lower currents the error increases up to 8% at 10 A.

In estimating the accuracy of a single measurement the error in counting fringes was taken as 0.5%, which corresponds to a shift of 1/50 fringe or a minimum detectable electron density of $2 \cdot 10^{14}$ cm^{-3}.

A larger uncertainty is associated with the determination of an effective arc length since the plasma inhomogeneities near the electrodes ar not well known. In order to investigate the effects of these cold layers and also to check the procedure for obtaining the effective plasma length we have varied the arc length by a factor of nearly two. However, no systematic deviations in the results of the two measurements were detected. Therefore the effective plasma length may be assumed to be within an uncertainty of about 1%, the geometrical distance between anode and cathode.

In conclusion it can be stated that 2λ – interferometry seems currently to be the most accurate method for an electron density determination in laboratory plasmas. An accuracy of 2% can be achieved with an appropriate interferometer and a well-defined plasma light source.

Nevertheless, results as, e.g., transition probabilities of Argon lines obtained from preliminary spectroscopic measurements, whose analysis was based upon the interferometrically determined electron densities, show to some extent systematic deviations from corresponding published data. The latter have been derived from H_β line profile measurements, which should, strictly speaking, yield electron densities of similar precision. At present we do not understand the reason for these discrepancies. Non-LTE effects are not responsible as we have concluded from separate measurements of the electron to gas temperature ratio. In our opinion there could be an inconsistency between the theory of plasma refractivity and the H_β line broadening theory. However, for a more precise statement it is necessary to compare both methods directly, i.e. to carry out simultaneous measurements of the electron density with both methods at the same plasma light source. These experiments have been started.

We thank J. Richter and W. L. Wiese for comments and suggestions. We also gratefully acknowledge fruitful discussions with E. Schulz-Gulde.

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