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Determination of the parameters of a plasma JET generated by a capillary discharge

Gabriela Sandolache,
Claude Fleurier,
Jean-Marc Bauchire,
Francois Gentils,
Vasile Zoita

Abstract A pulsed capillary discharge has been the subject of various experimental and theoretical studies. A jet of copper-hydrogen plasma with a cylindrical symmetry has been developed as a light source for spectroscopic measurements. The electron density of the plasma was obtained by using the H_β spectral line of the hydrogen component plasma. The electron temperature was determined by means of the Boltzmann method applied to the copper profiles emitted by the plasma jet. The copper and hydrogen lines were broadened principally by the Stark effect. The electron density of the plasma was found to be about 2×10^{17} cm^{-3} and the electron temperature about 20000K.

Key words capillary • electron density • Stark effect • temperature

Introduction

Copper lines are frequently observed in industrial plasmas and would be – in principle – well suited for temperature determination by the relative line intensity method because of the sufficient differences of their upper energy levels. It is then desirable to develop methods of plasma diagnostics using the emission spectrum of copper that is present in various types of industrial plasma devices.

An improved capillary discharge technique [1, 2, 6] enables the production of a plasma jet representing a radially symmetric light source. The paper represents the report of a first series of investigations on the plasma jet generated by a capillary discharge. The diagnostics of this plasma source has been carried out. The method consisted in generating an electrical discharge between two electrodes mounted at the two ends of a capillary tube in a hydrogen atmosphere. A storage capacitor, charged at high voltage, was used as the energy source.

The capillary discharge makes it possible to obtain a metal vapour plasma with the plasma components originating from the elements mixed within the wall of the capillary. There is, therefore, the possibility to obtain a metal plasma made up of elements that in the normal state are solid, their source being different than the electrodes of the discharge circuit. The copper-hydrogen plasma jet was produced by the ablation of the capillary wall consisting of a copper-embedded elastomer. Line widths and profiles have been frequently used for spectroscopic determination of plasma parameters. The electron density was measured by using the H_β line and the temperature by the method of relative intensities of cooper lines.

G. Sandolache✉, V. Zoita
National Institute for Lasers, Plasma and Radiation Physics,
P.O. Box MG 36, Magurele, R-76911 Bucharest, Romania,
Tel.: +401/ 7805385 ext. 1846, Fax: + 401/ 4231791,
e-mail: gabisan@alpha2.infim.ro

C. Fleurier, J.-M. Bauchire, F. Gentils
GREMI Laboratory, University of Orleans,
B.P. 6744, Orleans, France

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Methods

The plasma source was a jet emerging at the end of a capillary (length 60 mm, inner diameter 3 mm), whose inner wall consisted of a mixture of copper oxide and elastomer. A nozzle and one of the electrodes were attached at each end of the capillary. The second electrode was located at 90 mm with respect to the first one. The possibility to mix the metal atoms with those of chemical elements normally existing in the gaseous state has been sometimes of interest, e.g. for the determination of electron density from the line width of H_β. The elements, which should be introduced into the plasma, could be inserted into the inner wall of the capillary.

The two electrodes were connected to a high voltage capacitor discharge circuit. The plasma inside the capillary tube was heated resistively by the electric current flowing between the electrodes. The interaction of the discharge plasma with the tube wall has induced ablation of the capillary material, which, in turn, was added to the plasma. As a result, a high pressure was developed inside the capillary, causing a mass flow outward through the open nozzle. The capillary tube was contained in a strong plastic holder, to hold against the high pressure developed during the discharge. A schematic view of the plasma source is given in Fig. 1, showing the relatively simple design.

For the inner material of the capillary (thickness about 7 mm), the use of an elastomer was found to be favorable, in which the substance of spectroscopic plasma interest was embedded. These substances should mainly be elements or compounds with poor electrical conductivity such as oxides or hydroxides [6]. In these experiments, 10% copper oxide was embedded into the elastomer. Both electrodes were made from Cu-W alloy and carbon was chosen finally for the nozzle. The whole device shown in Fig. 1 was mounted inside the discharge chamber that could be evacuated in order to been able the change of the surrounding gas (hydrogen, in this case) and its pressure.

The energy was stored in a capacitor (C_0 = 17.5 μF), which could be charged up to 12 kV (Fig. 2). For the investigation reported here, the short-circuit ringing half-period was 140 μs because the discharge parameters were found to be optimal at about this value. A Rogowski coil connected to an oscilloscope measured the current pulse. A maximum current of about 3 kA was reached at about 70 μs.

The plasma jet was ejected through the open nozzle into the discharge chamber. Light emitted from the jet was collected by an optical system consisting of a pair of focusing quartz lenses (with the focal lengths of 0.50 and 0.75 m, respectively) to the entrance slit of a Czerny-Turner 0.75 m spectrograph (Acton model 750 with a 1200 lines/mm grating blazed at 500 nm). It had a specified reciprocal linear dispersion of 0.132 nm/mm in the first order of diffraction. The slit height and width was 1 cm and 50 μm, respectively. At the exit focal plane of the spectrograph an optical multichannel analyzer (OMA, EG&G model) was mounted. The OMA was equipped with a 512×512 pixels CCD detector with 16 bits-depth. The system allowed the recording of the image of the discharge with a 2 μs temporal resolution. The dimension of the CCD was 9.7×9.7 mm. The 2D square matrix CCD detector permitted the observation of cross sections of the plasma jet. The optical system had a magnification of 1.5, so that the 50 μm entrance slit of the spectrograph picked out a slice of the plasma jet of about 34 μm. By moving the discharge chamber parallel to the capillary axis (Z-axis) one was able to image slices from different axial locations along the jet on the entrance slit of the spectrograph. A personal computer was used for data acquisition. The experimental setup is presented in Fig. 2.

The measurements were made single-shot. All spectra were taken at different times during the first half period of the discharge. For the results reported here the emerging cylindrical symmetric plasma jet was observed side-on at a position of 1.5 mm from the end of the nozzle. The registration time moment was at 80 μs from the beginning of the discharge. A tungsten strip lamp was used to perform the absolute calibration of the spectrometric system.

Results

Radial distributions of the plasma parameters were obtained by a computer processed Abel inversion of the side-on measured data. The method of measurement was based on the dependence of Stark broadening of the hydrogen H_β spectral line (which was a constituent of the elastomer plasma) on the electron density [3]. The dependence

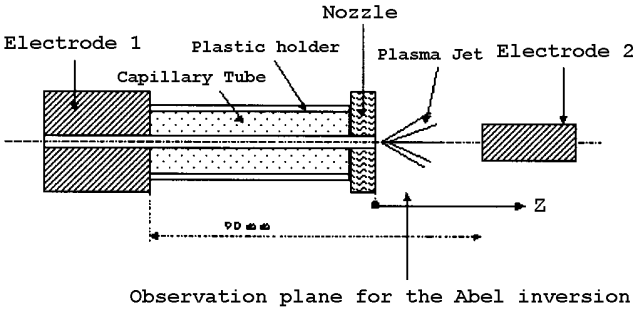

Fig. 1. The plasma source.

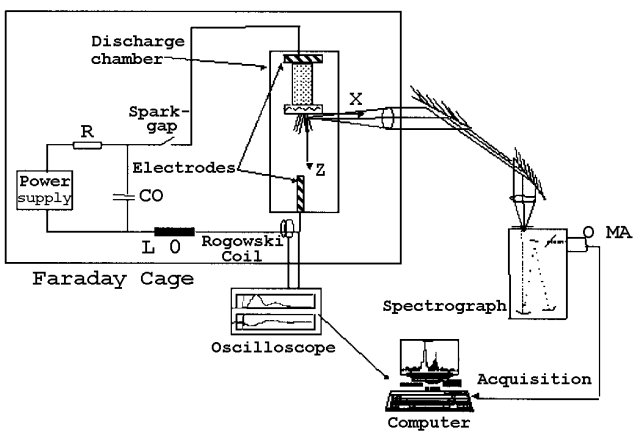

Fig. 2. The experimental set-up.

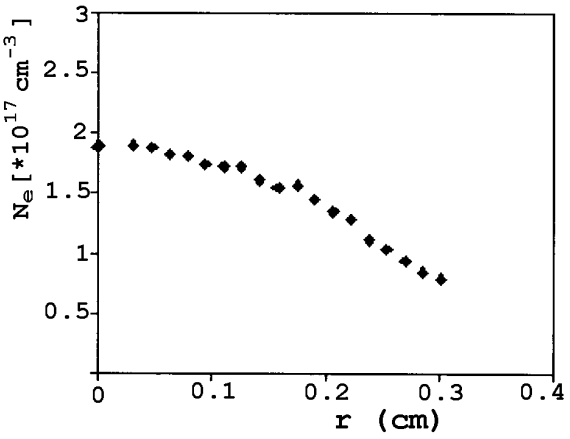

Fig. 3. Radial distribution of the electron density at 80 μs.

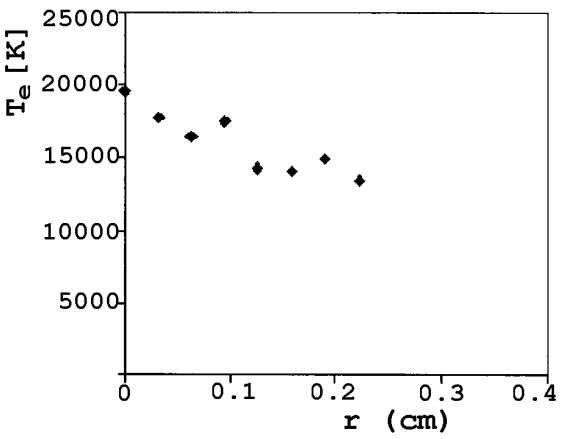

Fig. 4. Radial distribution of the temperature at 80 μs.

of the width of this line on the electron density was described and tabulated in the literature [4].

The measured values $I_\lambda(y)$, the spectral intensity integrated along the X direction, at various points along the Y-axis, were converted to the spectral radial distribution $I_\lambda(r)$ via an Abel inversion semi-analytic method that was performed on a computer for each wavelength. After the Abel inversion, each of the recorded lines was fitted by a Voigt profile to obtain the line width at a half maximum and the area of the line. The typical Voigt function parameter was given by the ratio between the parameter of Lorentz broadening and the parameter of Doppler broadening multiplied by $\sqrt{\log 2}$. For the present experimental conditions the Lorentz part of the recorded line profile was entirely due to Stark broadening. A standard iterative de-convolution procedure developed by Rompe and Steenbeck [6] for the Lorentz and Gaussian profiles was used. The Gaussian part was determined from the known apparatus function and calculated Doppler broadening. The value for the calculated Doppler width at 500 nm and 20000K was 0.006 nm. For the detection system the apparatus function width was 0.069 nm.

The procedure to obtain the electron density at a known temperature from the H_β profile consisted in drawing a set of theoretical profiles for different electron densities, all being normalized to the area of the profile. Then, the experimental profile was compared to the set of theoretical curves. From the best-fit profile the electron density was obtained. In a much simpler way the electron density, N_e, could be obtained from the width at a half maximum intensity of the H_β line. The dependence of the H_β line profile is nearly independent of the electron temperature and this makes the H_β line a good standard for the electron density determination.

The temperatures were obtained by applying the relative intensity method to some of measured intensities of CuI lines, e.g. 510.5 nm (transition: $4s^2\ ^2D\text{-}4p\ ^2P^0$, energies: 1.39–3.82 eV), 515.3 nm (transition: $4p\ ^2P^0\text{-}4d\ ^2D$, energies: 3.79–6.19 eV), 520.0 nm (transition: $4p'\ ^2F^0\text{-}5s'\ ^4D$, energies: 5.42–7.80 eV). Characteristic plots of the radial profiles of electron densities and temperatures, evaluated after Abel inversion of the side-on data, are given in Figs. 3 and 4, respectively, indicating a radially peaked pressure profile of the plasma jet at the exit of the nozzle. It follows that at 80 μs from the beginning of the discharge the jet plasma has maintained, at least partially, the expected pressure distribution inside the capillary.

Discussion

The light source described here gives the possibility of recording emission spectra of a copper plasma jet emerging from one end of the capillary discharge. The discharge geometry provides a good symmetry of the emerging plasma over a relatively large region.

The experimental values were obtained after the solution of the inversion problem (Abel inversion) and the de-convolution of the experimental spectral lines. The copper and hydrogen lines were found to be broadened mainly by the Stark effect. The electron density of the plasma was found to be about 2×10^{17} cm^{-3} and the electron temperature about 20000K.

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