Diagnostics of capillary light sources by means of line shape measurements and modeling

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Abstract. In this work the Hg visible triplet spectral lines were measured by means of Fourier Transform spectrometer and deconvoluted by Tikhonov’s regularisation method and line shape modelling. The lines were collected from Hg/Ar and Hg/Xe high frequency capillary lamps. In our previous work, the spatial plasma homogeneity of isotope Hg/Xe and Hg/Ar capillary lamps was investigated by means of tomography. The lamps were operated in different working positions – horizontally and vertically. In this work the spectral diagnostics of capillary light sources by means of spectral line shape measurements and modelling is presented to obtain plasma temperature. The results are compared with the results for spectral line shapes emitted from the spherical light sources. The splitting of spectral lines in magnetic field due to Zeeman effect was observed.

1. Introduction
The capillary light sources are obtained an increasing attention due to the need in compact high-intensity light sources for different applications where narrow line sources are needed [1]. Spatial homogeneity of the plasma and emission profile is important for the use of such light sources in precision measurements. In addition, capillary light sources are difficult to investigate due to the small dimensions of the source, and spectral line shapes are one of the possibilities to get useful information about plasma properties, for example, plasma temperature.

The Hg/Ar, Hg/Xe, Hg/Kr high frequency (HF) capillary discharge lamps (figure 1) were manufactured in our laboratory. In our previous work, the spatial distribution of atoms in Hg/Xe, Hg/Ar, Hg/Kr spherical and capillary lamps was investigated by means of tomography [2-4]. In [3] the radial profiles of excited atoms showed differences in dependence of the horizontal or vertical operation position. To understand the mechanisms of this phenomenon, more information about processes in capillary lamps is necessary. In this work the results of spectral line shape diagnostics of capillary light sources are presented. The diagnostics include measurements of the spectral line shapes by high resolution Fourier spectrometer and later deconvolution to get the real spectral line shapes. The real lines shapes are modelled to estimate the plasma

![Figure 1. Design of the capillary electrodeless light source - lamp together with HF generator.](image)
temperature and homogeneity. The results are compared with the results for spherical discharge lamps.

2. Experimental
The capillary light sources were filled with mercury isotope of 0.003 Torr pressure and argon, xenon or krypton of 2 Torr pressure. The length of the capillary was of 2 cm. The discharge size was of 500 μm in radius. The lamp contains spherical mercury reservoir to control the vapour pressure inside the lamp, and it was kept at the room temperature. The lamps were operated by HF electromagnetic field of 100 MHz frequency, capacitive coupled from outer electrodes located at the ends of the capillary [1].

In this work the emission spectral line shapes from the Hg visible triplet $7^3S_1-6^3P_{0,1,2}$ transitions (with the wave lengths Hg 404.7 nm, 435.8 nm, 546.1 nm respectively) were investigated for the Hg/Ar and Hg/Kr capillary lamps, operated in three different positions, horizontally, vertically with the Hg reservoir up and vertically Hg reservoir down. The spectral line profiles were registered also from spherical lamps of 1 cm diameter for comparison.

The spectral line shapes were registered by means of the Fourier Transform spectrometer Bruker IFS-125HR, allowing to register lines in the wavelength region 330-2000 nm. Examples of the registered spectral line shapes are shown in figure 2.

![Figure 2. Experimental profiles of Hg visible triplet spectral lines 404.7 nm, 435.8 nm, 546.1 nm, emitted from the capillary light source. Light source was operated in three different operation positions: horizontally, vertically, Hg reservoir up, and vertically, Hg reservoir down. Line splitting is due to the magnetic field in the generator.](image)

We can see that the FWHM of the experimental lines are about 0.06 cm$^{-1}$. In case of Fourier spectrometer the instrument broadening is on the same order as the width of real line shapes, emitted from low-pressure capillary discharge thus the deconvolution procedure has to be performed to get the real width without instrument distortion. The observed spectral lines are Zeeman split due to the magnetic field in the generator where the light sources are placed. The respective number of $\sigma$ and $\pi$ components can be observed. Clear difference of the intensities of the spectral lines in dependence of the operation position can be seen as already observed in our previous experiments [3].

3. Theoretical approach

3.1. Instrument function
The experimental instrument function of Fourier spectrometer is shown in figure 3. It was obtained registering 632.8 nm line from single mode He-Ne laser. For the detailed study of separate spectral line shapes, the influence of the approximation of instrument function of the Fourier spectrometer on the deconvolution results was estimated. The instrument function was approximated by Lorentz function, Gauss function, Voigt function and also the numerical data was taken for the calculations.
The best results were received for the approximation with the Lorentz function of 0.02 cm\(^{-1}\) FWHM which was used for the following calculations.

![Graph](image_url)

**Figure 3.** Instrument function of Fourier transform spectrometer and its approximation with Lorentz and Gauss functions.

### 3.2. Deconvolution method

Recovering the real spectral line profile from experimental line has always been an important problem in the high resolution spectroscopy. To study narrow emission lines like those emitted from capillary line sources, it is very important to deconvolute the instrument function to get the correct results for the plasma parameters. So-called problems of reduction to an ideal spectral device can be described by the first kind Fredholm integral equation:

\[
\int_{a}^{b} A(\nu - \nu_0) y(\nu_0) d\nu_0 = f(\nu), \quad c \leq \nu \leq d, \quad (1)
\]

Equation (1) is a convolution of an unknown real profile \(y(\nu_0)\) with instrument function \(A(\nu, \nu_0)\), where \(a, b\) and \(c, d\) are the limits of the real and measured (experimental) profiles accordingly. \(A(\nu, \nu_0)\) is the instrument function of the Fourier spectrometer in our case. As well known, equation (1) is an inverse ill-posed task, where direct solution is not possible. To obtain the real spectral line shape we use two methods: solving the inverse non-linear problem by the Tikhonov’s regularization method [5,6] and non-linear multi-parameter modeling, described in detail in [7]. Using Tikhonov’s algorithm, the initial ill-posed task (1) can be transformed to solution of following matrix equation:

\[
(\hat{A}^T \hat{A} + \alpha E) Y = \hat{A}^T \tilde{f},
\]

where, \(\alpha\) – parameter of regularization; \(A_{ij}\) – elements of NxN size matrix \(A\), which approximates kernel \(K(x, x')\); \(f_i\) – vectors – column with initial dates; \(Y_i\) – vector – column of solution. We use two different methods to determine the regularization parameter – method proposed by Kojdecki [6] and discrepancy method. After getting the real spectral line shape it was fitted to Gaussian profile. In the low-pressure discharge the main broadening mechanism is Doppler effect due to thermal motion of particles (the self-absorption is not present on the transitions under investigation). Thus the temperature of the radiating atoms was calculated from the FHWM of Gaussian profile [7].

### 4. Results and discussion

Figure 4 shows the example of the experimental and reconstructed line profiles using regularisation method. The wings of the real spectral line shape can be explained by the difficulties of the model to stabilise the solution by higher level of experimental uncertainties.
For the capillary light sources, the temperature of emitting atoms was estimated to be about 600 K what is much lower than in spherical discharge lamps. The difference in line widths in dependence of observation positions could not be observed.

5. Conclusions
In this work we measured with Fourier spectrometer the profiles of Hg 404.7 nm, 435.8 nm, 546.1 nm lines, emitted from isotopic Hg/Ar and Hg/Xe capillary (500 µm diameter). The real spectral line shapes were obtained by means of the Tikhonov’s regularisation method and mathematical modelling. The temperature of the emitting atoms was estimated. The calculations showed that the temperature of the atoms in the capillary light sources was about 600 K what is much lower than in a common spherical electrodeless discharge light source.

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