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Study of self-absorption in laser induced breakdown spectroscopy

M. Burger, M. Skočić, S. Bukvić *

University of Belgrade, Faculty of Physics, POB 368, 11000 Belgrade, Serbia

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ABSTRACT

We present a simple analytical expression for self-absorption correction of a spectrum recorded in the image mode of a CCD camera. It is assumed that two spectra are available, F_2 recorded with a back mirror and F_1 recorded without. The corrected spectrum F_0, free of self-absorption, is given by the following simple expression $F_0 = \frac{2F_1}{1+\frac{F_2-F_1}{GF_1}}$. We discuss the influence of noise on subsequent inverse Abel transform. An example, illustrating proposed method for self-absorption correction and Abel inversion is given in details.

1. Introduction

It is well known that plasma created by strong laser pulse interacting with a metal surface is a source of very clean metal spectra [1,2]. The plasma plume has axial symmetry in respect to the axis defined by the laser beam with plasma parameters varying along the radius. Electron density and electron temperature usually achieve their maximum values in the vicinity of the axis. Boundary of the plasma plume is difficult to determine since optical emission at the periphery gradually approaches values indistinguishable from the noise. In typical arrangements spectroscopic observations of the plasma are accomplished side-on. The detector collects light emitted by different regions of the plasma plume along the line of sight. In this way measured intensity represents 'integral value' of the light emission along the line of sight, see Fig. 1. If an imaging CCD is applied as a detector, then one can measure simultaneous emission along numerous lines of the sight, each at different wavelength λ and offset y in respect to the axis of the plume. Set of intensities captured by the CCD at the same wavelength λ but different y values (different lines of the sight) is commonly referred as the lateral profile, $F(\lambda, y)$[1]. Starting with the lateral profile and applying inverse Abel transform one can infer form of the radial emission function $\varepsilon(\lambda, r)$. At a first glance it appears to be a straightforward, easy to automate process. In practice, however, one has to overcome number of problems in order to obtain reliable radial emission function $\varepsilon(\lambda, r)$ starting from rough data $F(\lambda, y)$. Within this paper we propose a simple way to correct lateral profiles affected by self-absorption applying 'back mirror' approach.

2. Self-absorption issue

We suppose that plasma plume is symmetric in respect to the axis defined by the laser beam. In consequence, emission function $\varepsilon(\lambda, r)$ depends only on the radial coordinate r for given λ. If the plasma is free of self-absorption (at wavelength λ) the lateral profile $F(\lambda, y)$ registered by the detector corresponds to the forward Abel transform of the emission function, i.e.

$$F(\lambda, y) = 2\int_{r=y}^{r=\infty} \frac{\varepsilon(\lambda, r) r dr}{\sqrt{r^2 - y^2}} \equiv \int_{x=-\infty}^{x=\infty} \varepsilon(\lambda, r) dx. \tag{1}$$

The above relation is a definition of the forward Abel transform [3], under assumption that $\varepsilon(\lambda, r)$ approaches zero more quickly than $1/r$. The last equivalence in Eq. (1) relies on the following identities: $r^2 = x^2 + y^2$, $dx = \frac{rdr}{\sqrt{r^2-y^2}}$. When lateral profile $F(\lambda, y)$ is known, (recorded by a CCD detector, for example) the emission function $\varepsilon(\lambda, r)$ can be evaluated by the inverse Abel transform

$$\varepsilon(\lambda, r) = -\frac{1}{\pi}\int_{y=r}^{y=\infty} \frac{dF(\lambda, y)}{dy} \frac{dy}{\sqrt{y^2 - r^2}}. \tag{2}$$

If the plasma is not optically thin then recorded lateral profile $F(\lambda, y)$ is affected by self-absorption and inverse Abel transform is meaningless. Therefore, we need a way to check whether the plasma is free of self-absorption or not. A suitable approach is based on the use of duplicating or back mirror. This technique is presented and discussed in [4,5]. The idea of the method is to record two images, $F_2(\lambda, y)$ with back mirror and $F_1(\lambda, y)$ without. The 'back mirror' is in fact a system of a flat mirror and concave lens, properly positioned see Fig. 2, in order to provide perfect overlapping of the plasma plume with reflected image of the plume. In this manner reflected light is directed again through the plasma providing the way for estimating the amount of self-absorption.

* Corresponding author.

[1] In fact $F(\lambda, y)$ is a matrix representing captured image; every column of the matrix (constant λ) represents a single lateral profile $F_\lambda(y)$.

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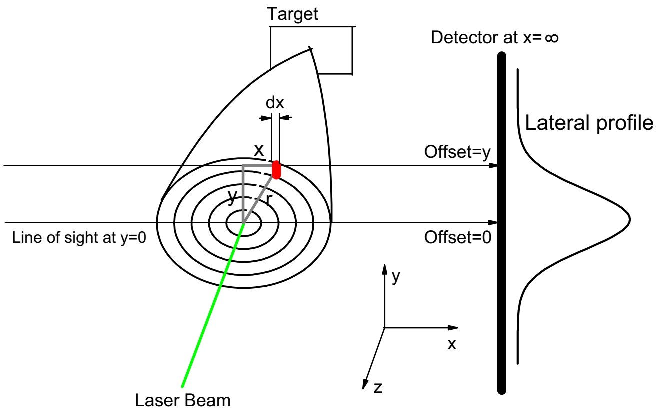

Fig. 1. Concentric circles mimic radial emission function $\varepsilon(r)$. Each point, $F(y)$, of the lateral profile corresponds to the integral emission along the line of sight at specific y. It is assumed that detector is placed at large distance from the plasma plume, at a region where emission function drops to zero. A plasma slice of the thickness dx at a position (x, y) contributes to the lateral profile as $dF(y) = \varepsilon(r)dx$ if the plasma is optically thin. See Section 2, Eq. (3) for optically thick plasma.

In addition to the emission function $\varepsilon(\lambda, r)$ we introduce axially symmetric absorption function, $k(\lambda, r)$, which is responsible for self-absorption. We consider the amount of light originating from a plasma slice, having thickness dx and lying on the line of sight y at the position x, coming to the detector, see Fig. 3,

$$dF_1(\lambda,y) = \varepsilon(\lambda,r)dx \cdot e^{-\int_x^\infty k(\lambda,r)dx}. \tag{3}$$

Term $e^{-\int_x^\infty k(\lambda,r)dx}$ quantifies absorption of the light emitted by the slice at the position (x, y), passing through the absorber $k(\lambda, r)$ and reaching the detector at the position $(x \to \infty, y)$. To handle the term $e^{-\int_x^\infty k(\lambda,r)dx}$ we introduce two auxiliary functions

$$urf(\lambda,x,y) = \int_0^x k(\lambda,r)dx$$
$$urfc(\lambda,x,y) = \int_x^\infty k(\lambda,r)dx.$$

The urf function determines the optical depth measured from 0 to x, while the $urfc$ function measures the optical depth from x to infinity. The main properties of these functions are discussed in the Appendix A. Therefore,

$$e^{-\int_x^\infty k(\lambda,r)dx} = e^{-urfc(\lambda,x,y)}.$$

The maximum value of the function $urfc$ is $2C$, where constant $C(\lambda, y) = \int_0^\infty k(\lambda, r)dx$ depends on the offset y and specific form of $k(\lambda, r)$.[2] If $C \ll 1$, the case when self-absorption correction is possible, expression (3) becomes

$$\begin{aligned} dF_1(\lambda,y) &\approx \varepsilon(\lambda,r)dx \cdot [1 - urfc(\lambda,x,y)] \\ &= \varepsilon(\lambda,r)dx \cdot [1 - \{C(\lambda,y) - urf(\lambda,x,y)\}]. \end{aligned} \tag{4}$$

[2] $2C$ is the total optical depth of the plasma plume along the line of the sight at the offset y.

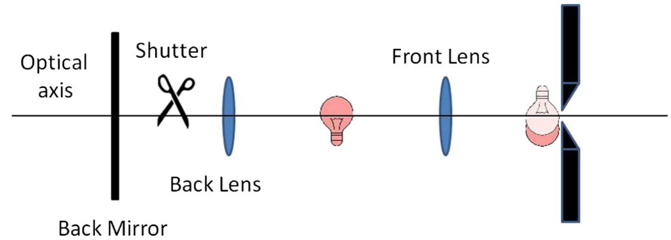

Fig. 2. Optical layout provides perfect overlapping of the plasma plume with reflected image of the plume. The electric bulb imitates plasma plume.

The total intensity over the line of the sight, at the offset y is

$$\begin{aligned} F_1(\lambda,y) &= \int_{-\infty}^{\infty} dF_1(\lambda,y) = [1 - C(\lambda,y)]\int_{-\infty}^{\infty} \varepsilon(\lambda,r)dx \\ &+ \int_{-\infty}^{\infty} \varepsilon(\lambda,r) \cdot urf(\lambda,x,y)dx. \end{aligned}$$

The last integral $\int_{-\infty}^{\infty}\varepsilon(\lambda, r) \cdot urf(\lambda, x, y)dx \equiv 0$ since the argument is an odd function as the product of even ε and odd urf functions. Finally, the above equation simplifies to the following form

$$F_1(\lambda,y) = F_0(\lambda,y)[1 - C(\lambda,y)] \tag{5}$$

where F_1 is the measured intensity over the line of the sight without back mirror, while $F_0(\lambda, y) = \int_{-\infty}^{\infty}\varepsilon(\lambda, r)dx$ is an intensity that we would obtain in the case of negligible self-absorption, see Eq. (1).

With back mirror in the place a certain portion of the light is directed back trough the plasma. Due to self-absorption just transmitted amount of the reflected light comes to the detector

$$F_2(\lambda,y) = F_1(\lambda,y) + G \cdot F_1(\lambda,y) \cdot T(\lambda,y). \tag{6}$$

The value $G < 1$ quantifies reflected fraction of the light, taking in account reflectivity of the mirror, transmission of the lens, solid angle etc., while

$$T(\lambda,y) = e^{-\int_{-\infty}^{\infty} k(\lambda,r)dx}$$

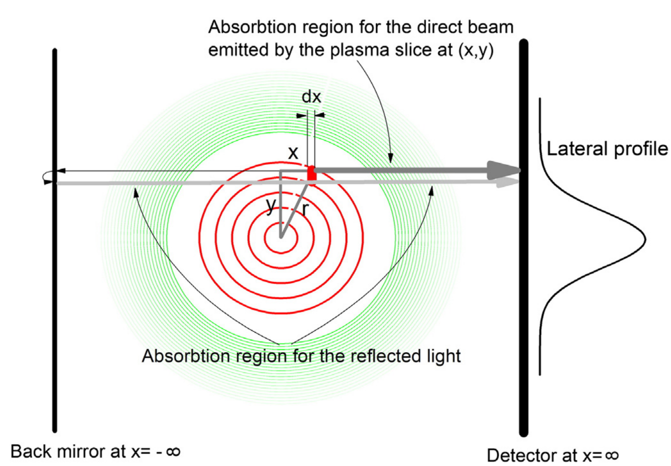

Fig. 3. For the purpose of simplicity emission area (red) and absorption area (green) are separated. With dark gray we indicate region of absorption for direct ray emitted by the plasma slice at (x, y). Corresponding optical depth is $\int_x^\infty k(\lambda, r)dx$. Light gray is the marked region of absorption for reflected beam, corresponding optical depth is given by $\int_{-\infty}^{\infty} k(\lambda, r)dx$ where $k(\lambda, r)$ is the absorption function. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)