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Data of plasma velocity obtained from Streak image processing of laser-induced breakdown

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Abstract. We present time resolved measurements of the laser induced plasma development in air. A Q-switched Nd:YAG laser is employed as the excitation source. The detection part of the acquisition system is based on a streak camera. We propose streak image processing technique based on a set of simple algorithms as a way to obtain estimations of plasma core and plasma plume instantaneous velocity. Using of the proposed technique enables us to obtain all data relevant for temporal analysis by a single shot excitation.

Key words: Laser induced breakdown spectroscopy – Streak camera – Image processing

1. Introduction

The formation of laser induced breakdown (LIB) refers to a plasma production by focusing an intense laser beam in a gas, liquid or solid target. Parameters of laser induced plasma depend on irradiation conditions, such as laser intensity, pulse duration, laser wavelength or ambient gas. To understand the process of laser induced breakdown it is required to obtain the detailed knowledge of the initial stages of various processes involving laser duration and irradiation, plasma formation and its expansion. The nanosecond laser pulse generates plasma through thermal and non-thermal mechanisms. Studying the plasma formation with a high temporal, spectral and spatial resolution is of a great interest and formation of laser induced breakdown plasma in air has been studied by many researchers Robledo-Martinez et al. (2008); Villagran-Muniz et al. (2001); Camacho et al. (2010); Kawahara et al. (2007); Pandey & Thareja (2010); Hori & Akamatsu (2008), including references therein. After the initial breakdown, plasma plume propagates towards the focusing lens Robledo-Martinez et al. (2008). The bright plasma core of the LIB plasma in open air is surrounded by a layer of cold, moderately ionized gas called the sheath Robledo-Martinez et al. (2008). Glow of plasma sheath, although fainter than the core, is also visible to the naked eye. An explosive plasma expansion induces optodynamic phenomena, i.e., the propagation of a shock, acoustical and ultrasonic waves. The optodynamic phenomena convey important information about the laser-material interaction. On the other hand, optical lines emission due to the electron transitions in laser-induced plasma can be used to obtain the crucial information for elemental analysis of samples in all three states. Studying the plasma formation with a high temporal and spatial resolution is therefore of a great importance in a laser-induced material transfer Bohandy et al. (1986); Mattle et al. (2012); Feinaeugle et al. (2012), pulsed-laser deposition Lunney (1995); Sánchez-Aké et al. (2012); Guzmán et al. (2013), and various industrial applications Bilmes et al. (2006); Lackner et al. (2004). The velocity field measurement of LIB plasma plumes in air has been the subject of various experimental techniques in recent years Koll et al. (2020); Shi et al. (2019); Nishihara et al. (2020). The influence of the delay time between the subsequent plasma images along the different directions are investigated in Shi et al. (2019). In this paper we propose streak image processing technique as a way to obtain estimations of plasma core and plasma plume periphery instantaneous velocity. Studies with similar aims were presented in references Robledo-Martinez et al. (2008); Villagran-Muniz et al. (2001); Camacho et al. (2010); Kawahara et al. (2007), but our method of data processing is quite different. Using the picosecond temporal resolution of our streak camera we analyze the initial time period after the laser induced breakdown. There are many well known simple image processing algorithms but the answer to the question which simple algorithms should be selected for use and how to combine them to achieve the goal desired in our study is not simple at all. After some considerations we discarded several techniques which seemed at the first glance as obvious solution for our problem. Namely, common image processing techniques are usually intended to be used on images seen in nature by a human observer. Streak images look like images, but they have some specific characteristics. First of all, they are spatial only in one dimension, the other dimension being the time. So, for example, general gradient methods for image edge detection would be misused if applied here and we discarded them.

2. Methods

A schematic diagram of the experimental apparatus is shown in Fig. 1. Time resolved LIB system implemented in our laboratory is based on Nd:YAG laser and Optical Parametric Oscillator (OPO; Vibrant 266). The OPO system, pumped by a pulsed Q switched Nd:YAG laser (Brilliant B) includes the second and fourth harmonic generator (SHG and FHG). In our experiments we used all outputs of this laser system as the excitation sources, but in this paper only the fundamental output at 1064 nm (pulse energy up to 270 mJ, pulse duration of about 5 ns) is used to create an optical breakdown in ambient air. One of advantages of using the excitation at 1064 nm is the fact that, for any kind of temporal analysis, we do not need to perform deconvolution of the laser pulse signal from streak image of plasma emission. The delay generator (Stanford Research Systems DG535) plays a significant role in the streak camera operation. Timing considerations regarding the laser pulse and streak camera synchronization are very important in our measurements Rabasovic et al. (2012, 2019), so we added a photodiode and digital oscilloscope to our experimental setup, Fig. 1. The plasma plume in air is obtained by focusing the laser beam using lens with the focal length of 40 mm. The OPO system is controlled by OPOTEK software installed on PC.

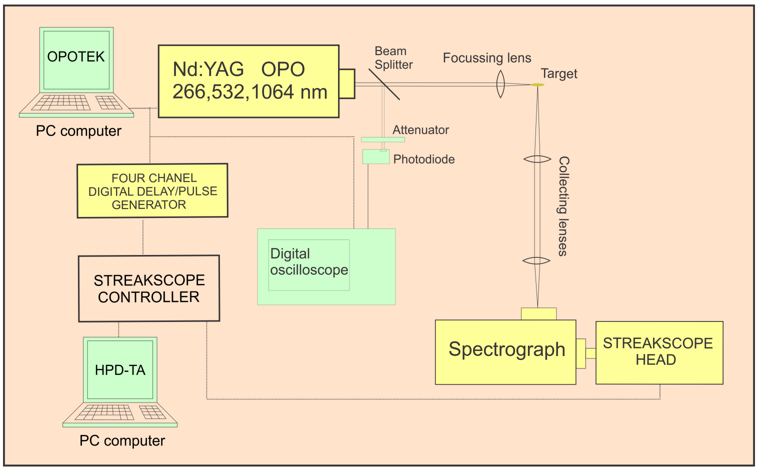

Figure 1. Setup for time-resolved laser induced breakdown measurements.

The optical emission from the plasma is collected by using a spectrograph (SpectraPro 2300i) and recorded with a Hamamatsu streak camera (model C4334) (Fig. 1). The streak images are time resolved thus enabling monitoring of temporal evolution of the ionic and atomic emission lines or spatial development of the plasma. The camera has the spectral range from 200 nm to 850 nm and time resolution up to 30 ps. The CCD chip has a resolution of 640 x 480 pixels. The data are acquired and analyzed using High Performance Digital Temporal Analyzer (HPD-TA) software, provided by Hamamatsu. Our earlier research of optical emission of plasma was limited so far to analysis of time resolved optical emission spectra acquired by the streak camera Sevic et al. (2011); Rabasovic et al. (2012, 2014). To make our study more comprehensive we saw the need for measuring the spatial distribution of plasma optical emission Rabasovic et al. (2019) and requirement for easy switching between the spectral and spatial measurement modes of our streak camera system soon became apparent to us. We performed a simple modification of our spectrograph that enables easy switching between the spectral and spatial measurement modes. Similar modification was already proposed and successfully used in the study of Siegel et al. (2005), where imaging device was ICCD camera. Our modification is different in a sense that optical alignment of target area to the streak camera slit needs special consideration and careful procedure. The spectrograph contains the triple grating turret. The diffraction gratings of 50, 150 and 300 gr/mm were installed. In the place of the 150 gr/mm grating we mounted the plain mirror. Now, if grating of 150 gr/mm is selected by HPD-TA software, than spectromemer projects the image of entrance slit to the streak camera. At the same time, collecting lenses project the image of the target plasma to the spectrometer entrance slit. In this way, streak camera instead of the image of the optical spectrum takes the image of the spatial distribution of the optical emission of the laser induced breakdown. The spectrograph entrance slit should be fully open to utilize as much as possible of the CCD camera active area. For measurements presented here other optical parts of the acquisition system were chosen so to have overall optical magnification of 0.6. In this case, the calibration procedure shows that 1 mm on the target position corresponds to 72 pixels of the CCD camera.

3. Results and discussion

Single-shot laser induced breakdown plasma emission spatial images analyzed in this paper are acquired in the direction perpendicular to the laser beam, as shown in Fig. 1. The streak image of the laser induced plasma (excitation at 1064 nm, energy of 51 mJ, peak intensity of 1.3 10^{11} W/cm^2) is shown in Fig. 2. The time axis is vertical, with zero time on the top of the image. The spatial axis is horizontal. The development of the plasma is seen on the streak image as vertical development (corresponding to a passing of time) of a narrow horizontal section of plasma optical emission, seen through the camera slit, along the direction of propagation of the laser beam. In other words, two dimensional (2 D) streak image corresponds to only 1-D spatial image, represented by rows of image matrix, the other dimension being the time. The streak images are often presented in pseudo-color, where different intensities are coded as different colors. However, the edges on such images could be misunderstood by an observer, so we present streak image as grayscale. Red points indicate the edges and peak values of plasma brightness, detected by our image processing algorithm. The laser beam is incident from the right-hand side of the streak image. As expected Robledo-Martinez et al. (2008), plasma plume expands towards the laser beam.

Our streak image processing algorithm is effective and easy to implement. First, the rows of streak image are mean filtered, using nine neighboring pixels, two times iteratively.

$$Lout[x] = \frac{\sum_{x=-4}^{x=4} L[x]}{9.0} \tag{1}$$

where $L[x]$ denotes intensity of streak image pixel with coordinate x.

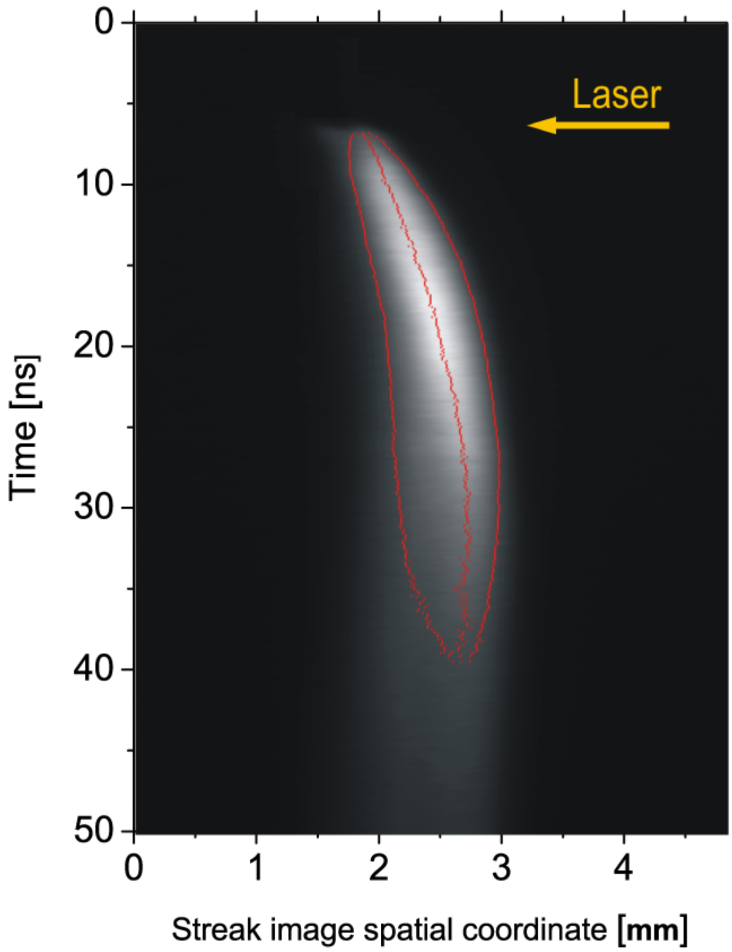

Figure 2. Streak image of the laser induced plasma (excitation at 1064 nm, energy of 51 mJ). Red points indicate the detected edges and peak values of brightness of the plasma plume.

The preliminary tests showed that mean filter is quite satisfying and simple method of filtering. We didn't use median filter because it is not suitable for Gaussian noise which is present on our streak images. It is generally true that median filter (often improved with several techniques like fuzzy logic, weighted coefficients, etc) performs better than mean filter. However, when there is too much Gaussian noise, a median filter blurs fine structures of an image and causes edge jitter and streaking Yang (1999). So, after some initial tries we have selected the mean filter which is simpler to implement than median. To alleviate effects of impulse noise, we introduced the following correcting rule:

if $((L[x] - mean) > threshold)$ then $L[x] = mean$
where *mean* is calculated as mean value of eight neighboring s:

$$mean = \frac{\sum_{x=-4}^{x=-1} L[x] + \sum_{x=1}^{x=4} L[x]}{8.0} \qquad (2)$$

After some experimenting, The *threshold* was set to be 5 % of value of maximal pixel intensity of analyzed streak image.

The problem of streak image noise is typically solved by using some kind of cumulative or integrating measuring streak camera techniques, based on repetitive laser excitation. By using the proposed filtering method it is possible to use a single-shot laser excitation.

All our streak images of plasma development are of the similar shape and the plasma contour is similarly positioned on the image, so it is possible to use a simplified algorithm for edge detection, specialized for our purpose. Namely, it is assumed that the right edge of plasma plume is detected when pixel intensities exceeds certain threshold above the averaged background, testing iteratively through the row of pixels, starting from the right side of the image. The algorithm is similarly conducted for the left edge of plasma plume. It is supposed that the pixel or pixels with the peak value of brightness of plasma core are identified when the value of pixel is equal to the calculated value of peak of that row. We did not limit the peak to the only one pixel because it would make a fitting of curve indicating the moving of plasma core more difficult.

The time diagrams of position changes of left and right side edge of plasma plume, and of the peak of plasma brightness, corresponding to the movement of the center of plasma core, are shown in Fig. 3. Note that the time ranges in Figures 3 and 4 correspond to the part of streak image where plasma expands. The diagrams are obtained by transferring the coordinates of pixels corresponding to detected edges and peaks of rows of streak image from Fig. 2. Time dependence of instantaneous-velocity of edges of plasma plume and peak brightness were also calculated from the same data set and shown in Fig. 4. Data corresponding to fitted curves from Fig. 3 were used for calculation to avoid nonexistent velocity fluctuations. Because the plasma plume is expanding and moving to the right at the same time, the velocity of the right edge is greater than the velocity of the center of the core, as shown in Fig. 4. As the expansion of the plasma plume ceases (for excitation energy of 51 mJ after about 10 ns) the velocity of right edge of plasma plume decreases. The velocity of the left edge of the plasma plume is smallest, because the direction of the plasma expanding is opposite to the direction of the plasma moving (Fig. 4).

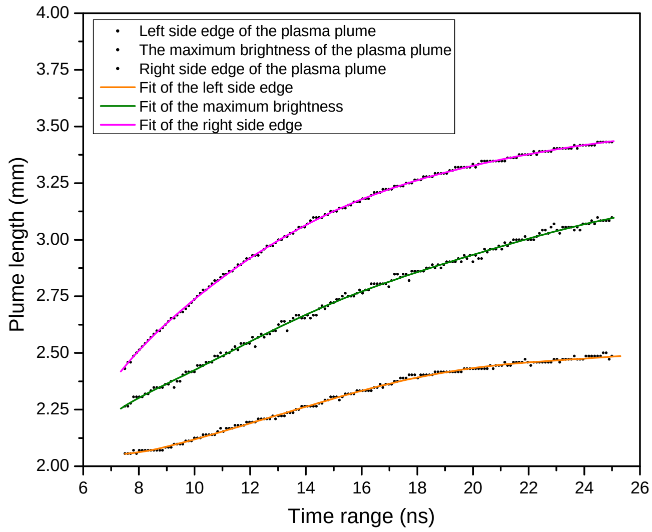

Figure 3. The time diagrams of moving of left side and right side edge of plasma plume, and of the peak of plasma brightness.

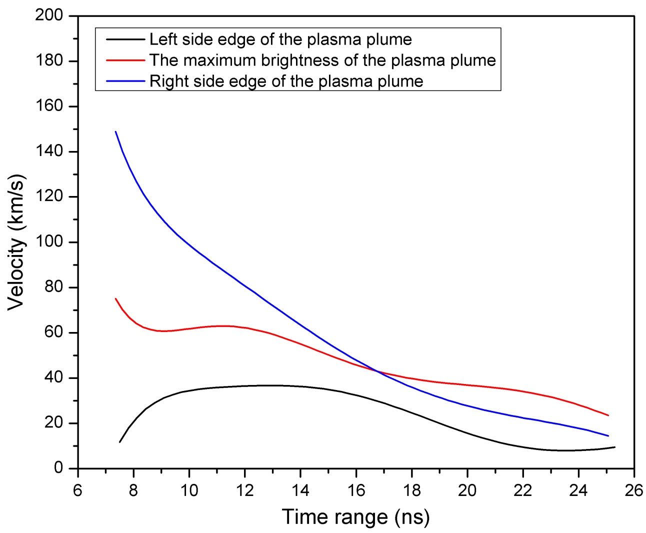

Figure 4. The time diagrams of instantaneous velocity of left side, right side (towards the laser beam) edge of plasma plume, and of the peak of plasma brightness.

Let us point out that, as stated in Introduction, our approach is quite different than the approaches in references describing investigations of laser produced plasma plume cited in our paper (before all, because their experimental equipment is more complex), so it is difficult to provide a quantitative comparison. There is no doubt that the results presented in cited references are more detailed and reliable, but similar investigations in cited references use fast framing cameras with two dimensional imaging, while our streak camera, although faster in time, has only one spatial dimension. Our study provides improved analysis of streak images based on image processing techniques.

It's important to highlight that the single-shot feature of our system has two dimensions: firstly, all the necessary data for calculating instantaneous velocity can be found within a single streak image, and secondly, the streak image can be acquired in a single shot thanks to the noise filtering method introduced in this paper.

4. Discussion and Conclusions

We have presented streak camera velocity measurements of the laser induced plasma development in air. We have described how to obtain estimations of plasma core and sheath instantaneous velocity by using streak image processing technique, based on image noise filtering and plasma sheet edge and plasma core peak brightness detection. So, we have provided, by data postprocessing techniques, alternative to much more complex experimental setups analyzing the laser produced plasma plume. All data relevant for temporal analysis were acquired by a single shot excitation. The presented method is suitable for plasma sheath velocity measurements from the very beginning of the laser induced breakdown by using a picosecond time resolution of our streak camera. For our future work we plan to include machine learning techniques for improving quality of streak images.

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