TEMPERATURE ESTIMATION IN THE EARLY STAGE OF LASER INDUCED PLASMA FORMATION RELAYING ON BLACK BODY RADIATION

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Abstract. We present experimental results of cooper plasma temperature measured in first couple of nanoseconds at the beginning of the laser-induced breakdown experiment. The experiment is conducted by Nd:YAG laser for two irradiances: 1.5×10^{11}, 3.0×10^{11} W/cm^2. The results indicate that LIP is in the state close to thermodynamic equilibrium while the laser illuminates the target. The values for temperature obtained from analysis of continuous spectrum are in agreement with the data available in the literature.

1. INTRODUCTION

Laser induced plasma (LIP) has been the subject of intensive research in recent decades (Hanh and Omenetto, 2010). LIP is created when the powerful pulsed lasers illuminate solid targets, liquids, and gaseous media. Depending on laser energy and pulse duration elementary processes taking place during illumination of targets are essentially different. For common nanosecond lasers interacting with metallic targets the process starts with heating of the solid target, followed by melting and evaporation of the target material (Bogerts et al. 2003, Lutey 2013, Singh and Narayan,1996). Due to high temperature the illuminated area of the target becomes bright with dominantly continuous spectrum. The evaporated material expands, absorbs laser radiation, heats up, and becomes a high-density plasma emitting in most cases continuous spectrum (Skocic et al., 2022).

The aim of this paper is to study plasma temperature evolution in the early stage of LIP when the laser still illuminates the plasma. All results are obtained by analyzing the continuous spectrum emitted by the plasma slice, see Fig.1.

2. EXPERIMENTAL SETUP

The experimental setup consist of a homemade chamber with high purity flat copper sample placed inside the chamber. The chamber is filed up with residual atmosphere at pressure ~ 0.02 mbar. To prevent drilling of the sample chamber is mounted on computer controlled x-y-z translation stage. The plasma was created by a focused laser beam from pulsed Nd:YAG, EKSPLA NL311-SH-TH, laser. Duration of the pulse (fundamental harmonic at 1064 nm wavelength) was 5.6 ns with repetition rate of 1 Hz. The spatial intensity profile of the laser spot on the target's surface had a top-hat form. The diameter of the spot was 0.2 mm. Dispersion system is based on Andor Shamrock SR-163 spectrograph with intensified CCD camera (2048 512 pixels) Andor iStar DH740-18F- 03, cooled down to 20 ^{0}C, as the detection system. The spectral range covered by the CCD chip, in this configuration, is from 200 nm to 750 nm. The plasma plume is projected on the entrance slit of the spectrograph with the collimating lens, with unity magnification, see Fig.1, left panel. The radiometric calibration (chamber window + collecting lens + optical fiber + CCD) is done relying on deuterium spectral lamp provided by StellarNet for UV and tungsten lamp for visible spectrum. Appropriate set of filters is used to prevent overlapping of the spectra coming from different spectral orders. The laser controller provides trigger signal which precedes actual firing of the Nd:YAG laser for $\sim$5 μs. In this way, the CCD camera can record the very beginning of the heating of the metal surface when the intensity of the laser is far below its maximum intensity.

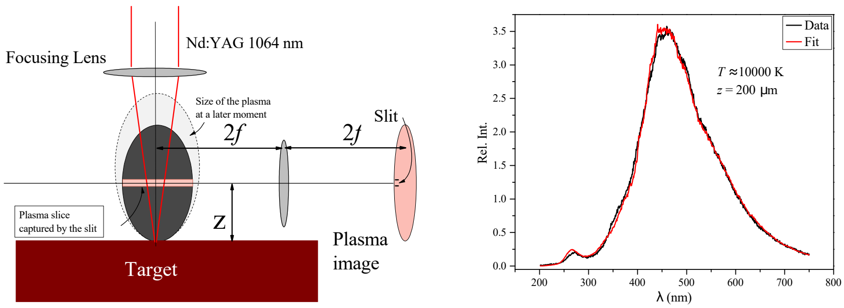

Figure 1: **Left:** Details of the experimental setup. The target is illuminated by the 1064 nm Nd:YAG harmonic. The optical system projects the image of the plasma on the spectrograph entrance slit, with unit magnification. **Right:** The black line represents the spectrum $I_r(\lambda)$ recorded by iCCD camera. The red line is the best fit of the product of Planck's spectrum $I_P(\lambda, T)$ and calibration curve $C(\lambda)$.

3. FITTING PROCEDURE

The radiometric calibration is conducted for the current experimental setup. With $C(\lambda)$ we denote calibration curve which is related to recorded spectrum $I_r(\lambda)$ and emitted spectrum $I_e(\lambda)$ in the following way: $I_r(\lambda) = I_e(\lambda)C(\lambda)$. It follows that

$$I_e(\lambda) = I_r(\lambda)/C(\lambda). \tag{1}$$

Comparing $I_e(\lambda)$ with black-body spectrum characterized by Plancks relation $I_P(\lambda, T)$:

$$I_P(\lambda, T) = \frac{A}{\lambda^5} \frac{1}{\exp(hc/\lambda kT) - 1}, \tag{2}$$

where A is a fitting constant, h is Planck's constant, c is speed of light, k is Boltzmann's constant, λ is wavelength, and T is temperature, one can estimate temperature of the emitter. However, due to noise present in $I_r(\lambda)$ and $C(\lambda)$ the ratio $I_r(\lambda)/C(\lambda)$ is for some recordings prone to large scatter at the end of intervals making fitting procedure inaccurate. A simple way to overcome this difficulty is to multiply Planck's spectrum by the calibration curve $I_p(\lambda, T)C(\lambda)$, and compare it, in sense of the least-squares method, with recorded spectrum $I_r(\lambda)$; see Fig.1, right panel. The best fit curve is obtained by minimizing $\sum_\lambda (I_r(\lambda) - I_P(\lambda, T)C(\lambda))^2$ where T is a temperature, the only fit parameter.

4. RESULTS AND DISCUSSION

Fig.2 provides an overview of our results. On the panel a) temporal profile of the ND:YAG laser is given. On the panels b) and c) we present temperatures for different positions from the target, for three distinct times. Different z values represent plasma slices at the position z, and width of 50 μm. Black squares, red circles and blue triangles stand for three different times, in respect to the trigger signal, at which the measurement is conducted. The times of measurements are marked with corresponding colors on the panel a). Values for temperature on panel b) are for laser irradiance of 1.5×10^{11} W/cm^2, and values on panel c) are for irradiance of 3.0×10^{11} W/cm^2.

For temperatures above 15 000 K, according to Planck's law, maximum of emission is in the UV part of the spectrum, at wavelengths below the detection range of the setup. In this case the fitting procedure relies only on the points from the red wing of Plancks curve, resulting generally in lower accuracy. Typical values of the relative errors associated to the temperature are ~ 20 %.

There is a noticeable difference between the two graphics (Fig.2 panel b) and c)), for two different laser irradiances. On the panel b), it can be seen that the temperature reaches a maximum at $t \approx 0$ ns, and then the plasma cools down. While the panel b) shows that the temperature of the plasma reaches a maximum value for $t \approx 4$ ns. This could be explained by the fact that plasma formed with a higher irradiance has higher density and therefore it can absorb laser radiation in later times much more intensively. Generally, the values for temperature are in reasonable agreement with the results from the model (Bogaerts et al., 2003).

5. CONCLUSION

In this work we present a technique for measurement of copper plasma temperature at the very beginning of the laser induced breakdown experiment, while laser still irradiates the plasma. The experiment is conducted by Nd:YAG laser for two irradiances: 1.5×10^{11}, and 3.0×10^{12} W/cm^2 at the residual atmosphere of 0.02 mbar. It is found that temperature plasma is in the interval 5000 - 60000 K. These values are in agreement with the data available in the literature obtained from the numerical simulations.

6. ACKNOWLEDGMENTS

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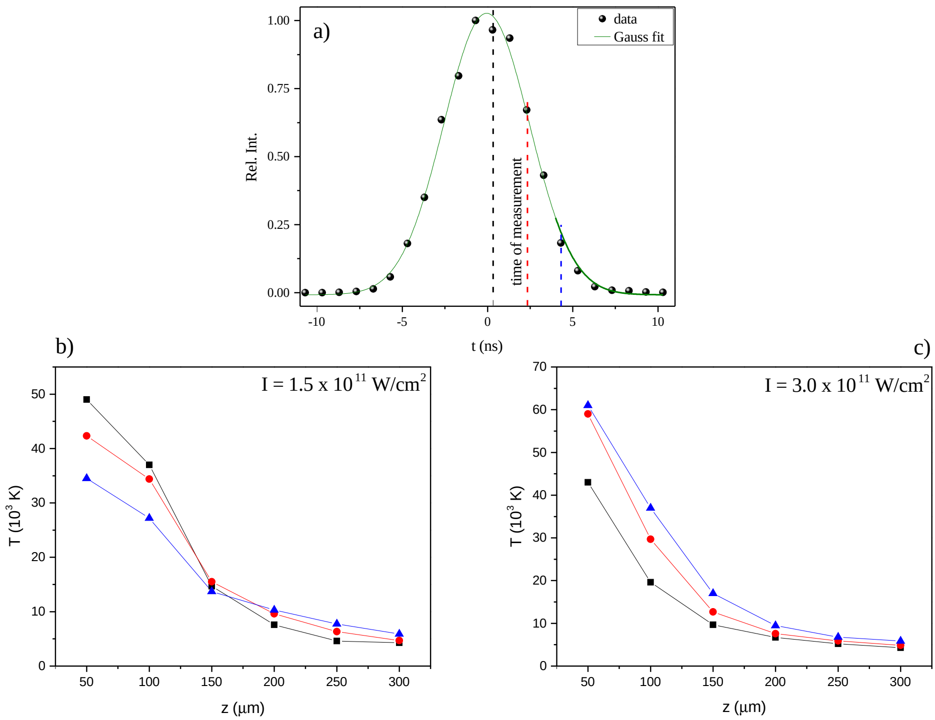

Figure 2: **Panel a)**: Black dots are measured Nd:YAG laser intensity in respect to the trigger signal. Green line is the best fit of to the Gauss function. Dashed lines represents the times at which the measurement was performed. The colors of the dashed lines are correlated with the colors of the points in panels b) and c). **Panel b) and c)** Set of temperatures for three time delays measured at different positions in respect to the target, for two laser irradiances.

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