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# Measurement of Electron Density and Temperature in Laser Induced Stainless Steel (SS) Plasma

Research Article

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**Abstract.** In this present work, electron temperature and electron density in Laser Induced Plasma (LIP) of Stainless Steel (SS) in air as a function of laser energy is presented. The emitted lines of Fe I at 351.0 nm, 373.5 nm, 397.5 nm are identified in LIP of SS. The electron temperature is obtained via Boltzmann plot from the relative intensity of these emitted lines. Electron density was determined from the stark broadening of Fe I lines at 375.5 nm. The electron density and temperature were measured at three different laser energies; 50 mJ, 60 mJ and 70 mJ. The electron temperature and electron density are found to be 0.145, 0.149 and 0.141 eV and $2.64 \times 10^{18}$, $2.66 \times 10^{18}$ and $2.54 \times 10^{18}$ $cm^{-3}$, respectively. The fall in both parameters can be explained due the plasma shielding effect at high energyof laser beam.

**Keywords.** LIBS; Plasma temperature; Electron density; Boltzmann plot; Stark broadening

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## 1. Introduction

*Laser Induced Breakdown Spectroscopy* (LIBS) is coming up as one of the reliable technique for the identification of the constituent atoms or molecules of any material in any physical states of the matter. The technique is free from any kind of sample preparation and nearly non-destructive or requiring very small amount of sample. LIBS system can be made portable at affordable costs for the field application as well as for the remote monitoring. LIBS has applications in multielemental material analysis [1], material processing [2] thin film deposition [3], biomedical research [4], art restoration [5], environmental monitoring [6], explosive residue detection [7] etc.

In LIBS technique, high intensity, pulsed laser of short duration is focused on to a material, when the focal intensity exceeds the breakdown threshold of the material present in the focal volume, it produces plasma. This is commonly termed as *laser induced plasma* (LIP). After the plasma formations, it begins to expand in the surrounding medium and cools down. During the process of plasma formation and cooling it emits radiation which originates from several mechanism: bremsstrahlung (free-free), radiative decay via recombination (free-bound), and radiative decay of excited atoms, ions, or molecules (bound-bound). By measuring the spectral emission from the laser induced plasma, quantitative information about the material can be obtained [8].

In order to optimize the LIBS technique, for quantitative analyses of the material, it is important to measure the plasma parameters such as plasma temperature and electron density. The present work deals with the characterization of the laser induced SS (stainless steel) plasma as a function of incident laser energy. The plasma temperature ($T_e$) has been estimated by using Boltzmann plot method and electron density from Stark broadening of the emitted lines [9].

## 2. Experimental Details

The schematic diagram of the experimental setup for the LIBS to study the SS sample is shown in Figure 1.

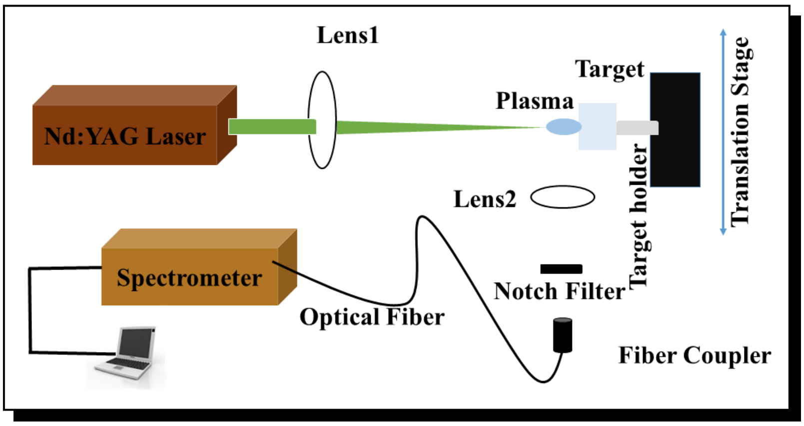


**Figure 1.** Schematic diagram of LIBS set-up in atmosphere

A second harmonic of Q-switched Nd: YAG laser (Quanta HYL 101) $\lambda = 532$ nm pulse width of 10 ns and repetition rate of 10 Hz is focused on a solid SS sample in air by using a convex lens L1 of focal length 15 cm. The sample is placed on to XY translation stage and translated at speed of 160.5 $\mu$m/sec so that every laser pulse is incident on the fresh location of the sample. This is necessary to avoid the crater formation for the uniformity on shot to shot basis. The emitted radiation from LIP is focused on the one end of the optical fiber by a lens L2 of focal length 5 cm. A notch filter at 532 nm is placed in front of the fiber to filter out scattered laser radiation. The other end of the fiber is connected to spectrometer which is interfaced with a computer to record the emitted spectrum. In order to study the effect of the laser pulse energy on LIP, the spectrumis recorded at three different energy i.e. 50 mJ, 60 mJ and 70 mJ.

## 3. Results and Discussion

Figure 2 shows the LIBS spectra of SS target recorded at various laser energy.

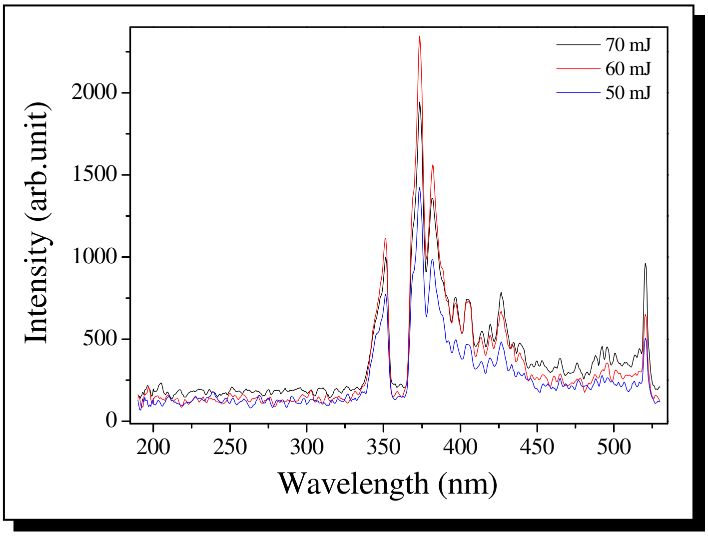


**Figure 2.** Optical emission spectrum from LIP SS target

The plasma temperature of SS plasma is estimated from the relative intensity of the lines using Boltzmann plot method. The lines of iron atoms at 351.0 nm ($3d^6 4s^2$-$3d^7(^4p)4p$), 373.5 nm ($3d^6(^5D)$ 4s4p ($^3P^0$)-$3d^6(^5D)$ 4s ($^6D$) 4d), and 397.5 nm ($3d6$(5D) 4s4p (3P°)-$3d6$(5D) 4s(6D) 5s) are identified in LIP of SS. It is assumed that the plasma is under the condition of local thermodynamic equilibrium (LTE) and emitted lines are free from self-absorption i.e., plasma is optically thin. Therefore, Boltzmann population distribution is applicable to determine thermodynamic parameters of this plasma. The plasma temperature can be calculated using the following relation [10, 11].

$$\ln\left(\frac{I_{nm}\lambda_{nm}}{A_{nm}g_{nm}}\right) = -\frac{E_n}{k_B T} + \ln\left(\frac{hcN}{U(T)}\right), \tag{3.1}$$

where $I_{nm}$, $g_{nm}$, $A_{nm}$, $\lambda_{nm}$ and $E_n$ are the intensity, statistical weight, transition probability wavelength and energy of the upper state $n$ and $U(T)$, $N(T)$, $k_B$ and $T_e$ are the partition function, total number density, Boltzmann constant and electron temperature, respectively. The plot of $\ln\left(\frac{I_{nm}\lambda_{nm}}{A_{nm}g_n}\right)$ versus the upper level energy $E_n$ is called Boltzmannplot. The slope of this straight line is equal to $-1/k_B T_e$ and thus $T_e$ is can be evaluated without knowing the value of partition function $U(T)$. For the calculation of plasma temperature, the data corresponding to the selected spectral lines have been obtained from NIST data base. All these relevant spectroscopic parameters are listed in Table 1. The Boltzmann plots at all the three laser energy are shown in Figure 3. The electron temperature from this found to be 0.145 eV, 0.149 eV and 0.141 eV for laser energy 50 mJ, 60 mJ and 70 mJ, respectively.

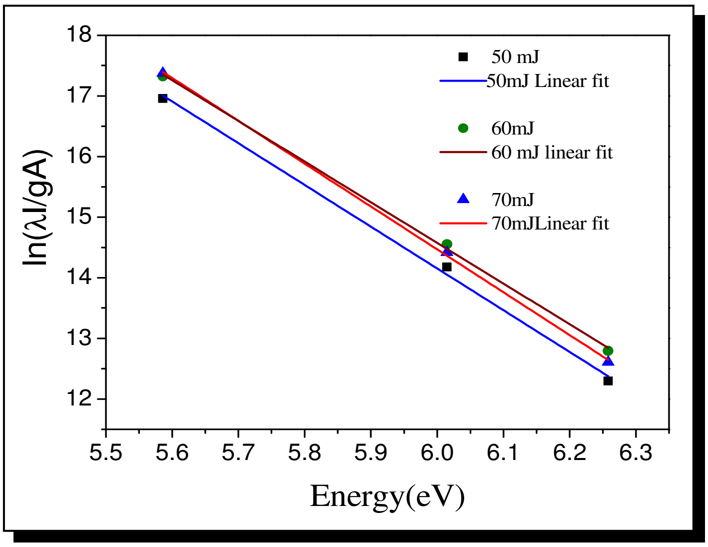


**Figure 3.** Boltzmann plot at different laser energy

**Table 1.** Spectroscopic data for observed spectral lines of neutral iron lines

| Wavelength (nm) | $E_n$ (eV) | $g_n$ | $A_{nm} * 10^8(\text{s}^{-1})$ |
|---|---|---|---|
| 351.0 | 6.015 | 3 | 0.062 |
| 373.5 | 6.258 | 9 | 0.270 |
| 397.5 | 5.586 | 7 | 0.001 |

Electron density is another important parameter for plasma characterization. This has been calculated using Stark broadened profile of Fe I line at 373.5 nm. Stark broadening occurs due to the coulomb interaction of the emitting atoms with the free electrons and ions in the plasma. The electron number density is related to the FWHM of stark broadened lines and is calculated by the following expression [11]

$$\Delta\lambda_{1/2} = 2w[N_e/10^{16}] + 3.5A[N_e/10^{16}]^{1/4} \times [1 - 3/4(N_D)^{-1/3}]w[N_e/10^{16}], \tag{3.2}$$

where $w$ (nm) is the electron impact parameter, $A$ (nm) is the ion broadening parameter, $N_e$ (cm$^{-3}$) is the electron density and $N_D$ is the number of particles in the Debye sphere. The first term in the equation refers to broadening due the electron and the second term is attribute to the ion broadening which is very small compared to the first term of equation (3.2), so it can be neglected and the equation can be written as follows:

$$\Delta\lambda_{1/2} = 2w[N_e/10^{16}]. \tag{3.3}$$

Figure 4, shows the profile of iron spectral line at 373.5 nmand the lorentzianfit on it. The electron density is estimated from the observed FWHM of the fitted line using equation (3.3). The electron densityobtained at 50 mJ, 60 mJ and 70 mJ is $2.644 \times 10^{18}$, $2.611 \times 10^{18}$ and $2.454 \times 10^{18}$ $cm^{-3}$.

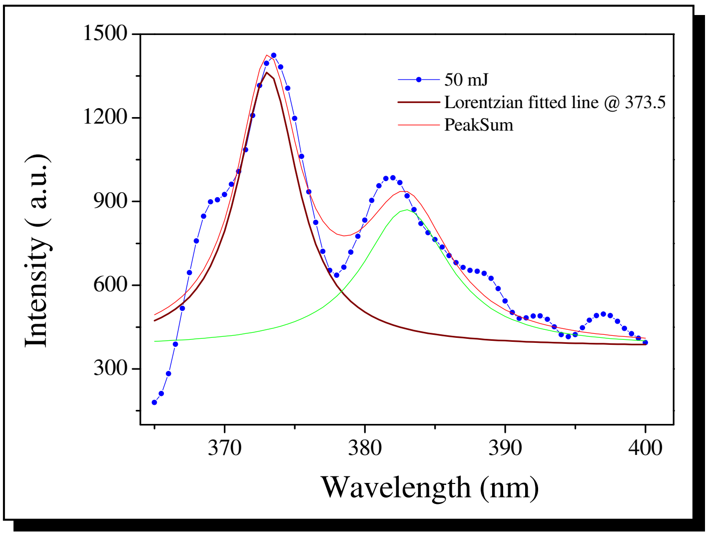


**Figure 4.** Starkbroadened Fe I line at 373.5 nm

In Table 2 the variation of both the plasma parameters are tabulated as a function of laser energy. From the LIP spectra of Figure 2, it is observed that intensity of the emitted lines first increases with laser energy and after that it decreases. Similar trend is observed for the measurement of plasma temperature. This may be due to the plasma shielding effect. For the nano second laser pulse, the later part of the pulse reheated the plasma which causes the enhancement of the signal intensity as well as increases it temperature. After reaching at a certain energy, due to the plasma shielding, incoming laser energy can not propagate to the sample surface further so mass ablation reduces which causes the decrease in signal intensity and also in plasma parameters [12].

**Table 2.** Variation of plasma parameter with the incident laser energy

| Laser energy (mJ) | Plasma temperature $(T_e)$ eV | Electron density $(N_e) * 10^{18}$ |
|---|---|---|
| 50 | 0.145 | 2.644 |
| 60 | 0.149 | 2.611 |
| 70 | 0.141 | 2.459 |

## 4. Conclusions

In the present paper, atomic spectrum of Fe I lines of SS sample from Laser Induced Plasma is recorded. The line intensities of Fe I spectral lines are used to calculate the plasma temperature and stark broadened profile of 373.5 Fe I line for estimation of electron density. Both the plasma parameters are studied as function of incident laser pulse energy.

Plasma temperature was found to be 0.145 eV, 0.149 eV and 0.141 eV for the energies at 50 mJ, 60 mJ and 70 mJ, respectively. The electron density found to be $2.644 \times 10^{18}\ \text{cm}^{-3}$, $2.611 \times 10^{18}\ \text{cm}^{-3}$ and $2.459 \times 10^{18}\ \text{cm}^{-3}$. The fall down in the plasma temperature and electron density at high energy is expected to be due to the plasma shielding effect.

## Competing Interests

The authors declare that they have no competing interests.

## Authors' Contributions

The authors wrote, read and approved the final manuscript.

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