Plasma Parameters Generated from Iron Spectral Lines By Using LIBS Technique

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Abstract.
An interesting LIBS technique was used to investigate the optical emission spectral plasma of iron metal properties. To generate plasma from the surface Fe, Q-switched Nd-YAG laser with wavelength 532 nm and a focal length 10 cm was used with different energies (500-800) mJ. Then plasma parameters were calculated; electron density \( n_e \) ranged between \((0.92-1.4) \times 10^{18}\) cm\(^{-3}\), the electron temperature \( T_e \) was in the range of \((2.19-2.59)\) eV. These calculations were done using Boltzmann’s plot and the Stark broadening respectively depending on the experimental spectrum, and followed up to estimate the others plasma parameters, Debye length \( \lambda_D \), frequency \( f_p \) and the Debye sphere \( N_D \). Results indicate that plasma parameters are proportional to the energy of laser due to the increase in the intensity of spectral lines energy, and that plasma shielding of iron increases with laser energy in the range of (3.2-4.3).

Keywords: Laser-induced plasma (LIP), Iron Plasma parameters, Optical emission spectroscopy (OES).

1. Introduction

Laser-induced breakdown spectroscopy (LIBS) is a flexible and powerful tool for elemental studies in a wide field in science, medicine, laser-plasma sources inertial confinement, and laboratory astrophysics [1]–[4]. To forming plasma using the ablation process and using pulse period lasers (> 1 ns), in this process, the laser light interacts with the material resulting in quick ionization of the target surface. Where incident plasma on a time scale short approach with the pulse duration, the laser light is absorbed by the electron target and appears as a plasma which isothermally after that the laser pulse collisions with material atoms [5] [6]. To study laser Fe plasma, we used the LIBS mechanism such as previous studies [7]. Produce and measurement the visible spectrum emissions Fe material plasma used Nd: YAG laser radiation dependence of Laser-induced plasma visible...
emission spectroscopy pulse laser at intensities ($1 \times 10^4$ - $6 \times 10^4$) (a.u). The spectral line intensities allow the calculation of the ion/electron distributions, plasma potential, electron temperature, and electron density in the air.[8] The emission of radiation from a plasma provides much information about the plasma properties, (OES) best method to evaluate plasma parameters to predict the radiation emission from a plasma [8]–[11].

Generally, spectral methods try to found relationships between the plasma parameters ($\lambda_D$, $N_D$, $n_e$, and $T$) and the radiation of spectral lines, such as the emission or absorption intensity appear from material Fe and the broadening or shifting of the spectral lines. All methods depend on the system of spectroscopy and using it for different applications [12].

In this system used different techniques to calculate the properties of Iron (Fe), electron temperature, and density were determined by spectroscopic, including the lines intensities emission, line-line ratio, and Stark broadening techniques [13], [14].

The information gains over from the plasma spectrum resulting in Iron pure material during the production process spectrum allowed to determine the properties of the plasma. These parameters were sure correlated with the structure of the material (atoms, ions, and electrons). T.Hussain, M.A.Gondal analyzed the properties of plasma that was produced in a pulsed laser ablation system [15]–[17].

All plasmas emitted by radiation depending on their plasma parameters and material composition. (OES) is using to measure and analyze plasmas radiation to comprehend the plasma properties by fiber probe without contact with the plasma. It’s considered an applicable measurement technique for laser absorption lines radiation where can measure a very small range of plasmas. So, consider remote diagnostic. Where represent the general optical method to treat the radiation. It has a lens to collect and focus the visible light on the surface material and can measure by it the temperature and the density of electron, etc. By using the information from optical emission spectroscopy and NIST Atomic Spectra Database Lines Data can determine the properties of Iron [18]–[21].

2. Experimental setup
In this work, iron samples were prepared as shown in Fig.1, in details 3g of iron powder with purity 99.99% was pressed inside stainless steel mold, the pressing performed at room temperature by a hydraulic piston with a compression strength of approximately 6 tons, Iron pellets were obtained with 5mm thickness and 10 mm in diameters as shown in Fig.2.

![Iron powder material with a purity of 99.99% before pressing.](image1)

**Fig.1: Iron powder material with a purity of 99.99% before pressing.**

![Iron pressed per tablet.](image2)

**Fig.2: Iron pressed per tablet.**

Using LIBS system to generate plasma, consist a Q-switched Nd: YAG pulsed laser, wavelength ($\lambda=532$) nm at different energies (500-800) MJ, also very accurate lens (UV/vis collimating lens 200-2000) was used to avoid delay mechanism and to Preserver of the spectrum generated from plasma as excitation, and focusing it on the sample (Fe), optical fiber (QP600-2-SR-BX, 600um premium fiber solarization resistant) was connected to the spectrometer optics (200-1025) nm see fig (3). The second end of the fiber was fixed close to the sample with angle 45° in to collect and transfer plasma emission. plasma emission.
3. Results and discussions

3.1. Emission spectra

Q-switched Nd: YAG laser technique used to produced induced plasma by bombarding Fe target at 532 nm, the process occurs with different pulse laser energies of (500, 600, 700, and 800) mJ.

The pulsed laser deposition technology uses the high energy laser pulse for heating the target. The depth, in the material which the laser penetrates, depends on the laser wavelength and the material properties.

The laser electric field in this material volume excites electrons (actually tears them away from the atomic cores), which then oscillate in the laser beam electromagnetic field. This leads to a collision of the electrons with the target material grid, resulting in heating the material.

A so-called “plasma plume” generates, which is an aggregation of atoms, molecules, clusters, ions, and electrons forced out from the target by the laser beam. The emitted plasma spectra for each energy was appears and recorded when pulse laser incident on the iron pellet and generated high intensity. The emission spectra of iron plasma increase with laser energy [15].

Table (1) list the lines of Fe at upper and lower energies, the strong transitions happen in the FeI and FeII illustrate in the table and one weak transitions line was noted at FeV.
Table 1. Illustrate the strong emission lines of FeI, FeII, and one-line FeV from the reference database [23].

| Ions | Wavelength (nm) | $A_{ki}$ (S$^{-1}$) | $E_i$ (cm$^{-1}$) | $E_k$ (cm$^{-1}$) | Transitions | Lower level | Upper Level |
|------|-----------------|---------------------|------------------|------------------|-------------|-------------|-------------|
| FeII | 283.15          | 7.6e+07             | 25787            | 61093.406        | 3d\(6(3P^0)4s\) | 3d\(6(3P^0)4p\) |
| FeI  | 298.22          | 3.47e+06            | 24118.819        | 57641.001        | 3d\('6^2s^4p^'1P^0) | 3d\('6^2s^4p^'1P^0) |
| FeI  | 321.37          | 1.09e+06            | 24338.767        | 55446.008        | 3d\('6^2s^4p^'1P^0) | 3d\('6^2s^4p^'1P^0) |
| FeI  | 328.6           | 5.99e+07            | 17550.181        | 47966.585        | 3d\('6^2s^4p^'1P^0) | 3d\('6^2s^4p^'1P^0) |
| FeI  | 357             | 6.03e+06            | 19552.478        | 47555.610        | 3d\('6^2s^4p^'1P^0) | 3d\('6^2s^4p^'1P^0) |
| FeI  | 373.13          | 3.37e+06            | 21038.987        | 47831.153        | 3d\('6^2s^4p^'1P^0) | 3d\('6^2s^4p^'1P^0) |
| FeI  | 381.18          | 2.52e+06            | 22249.429        | 48475.686        | 3d\('6^2s^4p^'1P^0) | 3d\('6^2s^4p^'1P^0) |
| FeI  | 396.31          | 1.5e+07             | 26479.381        | 51705.014        | 3d\('6^2s^4p^'1P^0) | 3d\('6^2s^4p^'1P^0) |
| FeI  | 406.53          | 1.7e+07             | 27666.348        | 52257.346        | 3d\('6^2s^4p^'1P^0) | 3d\('6^2s^4p^'1P^0) |
| FeI  | 413.62          | 4.7e+05             | 803.1            | 24972.8          | 3d\('6^2s^4p^'1P^0) | 3d\('6^2s^4p^'1P^0) |
| FeI  | 419.7           | 3.0e+05             | 23783.619        | 47606.114        | 3d\('6^2s^4p^'1P^0) | 3d\('6^2s^4p^'1P^0) |
| FeI  | 426.4           | 1.62e+06            | 27166.820        | 50611.261        | 3d\('6^2s^4p^'1P^0) | 3d\('6^2s^4p^'1P^0) |
| FeI  | 438.27          | 1.54e+06            | 28819.954        | 51630.178        | 3d\('6^2s^4p^'1P^0) | 3d\('6^2s^4p^'1P^0) |

Fig. 4: The Plasma Intensity lines function to the wavelength at different Energies.

3.2 Measurement of plasma parameters ($T$, $n_D$)

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This article aims to study the effect of applying different laser energies on plasma parameters such as electron temperature, electron density, and intensity of the spectral lines that form on the iron surface under plasma conditions.

Analysis of plasma parameters such as electron number, density, and temperature of the species all these parameters evaluate by used spectroscopic performance. We must consider the thermodynamic equilibrium exists so explained the properties of the plasma such as the population of energy levels and speed distributions of particles through the temperature. The best way to determine the electron energy from the relative intensities of the FeI lines utilizing the Boltzmann plot method. This way is dependent on the local thermodynamic equilibrium (LTE), where assuming the kinetic temperature and excitation temperature are equal to [22]:

\[
\ln \left( \frac{\lambda}{h c A g} \right) = - \frac{\Delta E}{k T_e} \quad \text{Slope} = - \frac{1}{k T_e} \quad (1)
\]

where \( I \) is the spectral line intensity of the emission line, \( \Delta E \) is the difference between two energy level (\( E_i \) and \( E_j \)), \( k \) is the Boltzmann constant, \( T_e \) is the plasma electron temperature, \( c \) is the speed of light, \( h \) is plank’s constant, \( g \) is the transition probability, \( g \) is the statistical weight of the level and \( \lambda \) is the wavelength of spectral lines.

To calculate the electron temperature (\( T_e \)) can use the equation of ionization spectral for two lines

\[
T_e = \frac{E_1 - E_2}{k_B \ln \left( \frac{\lambda_2 l_2 g_1 A_1}{\lambda_1 l_1 g_2 A_2} \right)} \quad (2)
\]

Where \( I, g, A \) and \( \lambda \) represent the intensity, statistical weight, absorption oscillator strength and wavelength, and \( E \) is the excitation energy of one line.

Electrons density represents the number of free electrons per unit volume evaluate using the Suha Boltzmann equation utilizes spectral lines of the Fe ionization stages. The Suha- Boltzmann equation is given as

\[
n_e = \frac{l_1}{l_2} \times 6.04 \times 10^{21} (T)^{3/2} e^{\left( \frac{-E_k - E_l - l_2}{k_T} \right)} \times T_e^{3/2} \quad (3)
\]
Where \((E_k, E_l)\) represents the energy of levels (1 and 2) gives a straight line with slope equal to equation 1. The plasma temperature can determine by graph slope. To determine the lines iron uses the different spectroscopic parameters and taken from the NIST database, which is listed in Table 1 [22].

The ionization energy of atoms in Fe target we can get from,

\[
I_z^2 = \frac{I_2 \lambda_2}{g_2 A_2}
\]

\(I_z\) is the ionization energy in eV, \(g_2\) is the statistical weight of transition from level 2 to level 1, \(\lambda_2\) is the wavelength of transition from level 2 to level 1 and \(A_2\) is a transition probability of transition from level 2 to level 1.

While the plasma frequency is calculated from the equation [5]:

\[
f_p = \frac{n_e e^2}{m_e e_0}
\]

The plasma frequency is one of the most important parameters. Debye length represents the distance of the individual particle effect another charged particle in the plasma, this parameter \((f_p, \lambda_D)\) is a fundamental characteristic of the behavior plasma. Debye length \((\lambda_D)\) is directly proportional to the square root of the electron temperature and inversely to the electron density according to Ref. [9], [23]:

When applying the Nd: YAG laser at 532 nm. It has been observed that electron temperature varies from 2.19 eV to 2.36 eV as a function of energy changed from (500-800) mJ.

The equation of a straight line with a gradient \((-\frac{1}{kT_e}\)) and the plots a graph of \(\ln \left( \frac{\lambda}{h c A g} \right)\) against \(E\) for several measured emission lines with the plasma temperature can be determined from figure 5.
Fig. 5 Boltzmann Plot derived from LIBS of Iron in air.

Fig. 6 the variation of (Te) and (ne) versus the laser energy for Fe in air.
Table (2) display the calculated electron density \( (n_e) \), electron temperature \( (T_e) \), Plasma frequency \( (f_p) \), and Debye number \( (N_D) \). For Fe: I target at different applied pulse laser energies. All calculated plasma parameters under criteria conditions

Table 2: Plasma parameters for Fe: I in the air with different laser energy

| E(mJ) | T (eV) | FWHM | \( n_e \times 10^{18} \) (cm\(^{-3}\)) | \( f_p \times 10^{12} \) (Hz) | \( \lambda D \times 10^{-6} \) (cm) | \( N_D \times 10^3 \) |
|-------|--------|------|-------------------------------------|----------------------------|----------------------|-----------------|
| 800   | 2.36   | 1.81 | 1.4                                 | 1.0E+13                    | 3.2                  | 1.9             |
| 700   | 2.28   | 1.78 | 1.3                                 | 1.0E+13                    | 3.7                  | 2.7             |
| 600   | 2.19   | 1.25 | 9.4                                 | 8.7E+12                    | 4.1                  | 2.8             |
| 500   | 2.19   | 1.32 | 9.2                                 | 8.5E+12                    | 4.3                  | 3.3             |

4. Conclusions

Q-switched Nd: YAG laser was successfully used to bombard the iron target with a wavelength of 532nm, the incident laser lead to heating of the target and produced plasma plum. this technique allowed for the calculation of plasma parameters such as density, and temperature of electrons based on the experimental results of the optical emission spectrum (OES) by connecting them with Boltzmann’s plot and the Stark broadening. Different experimental spectrums were obtained from the target bombardment with different laser energies and for each condition \( T_e \) and \( n_e \) were estimated. The emission lines intensities appeared at the laser peak energy and it was found that increasing the laser energy from 500 mJ to 800 mJ increased the intensity of the lines due to the increases in electron extraction as a result of energy absorption increasing, thus leading to more electrons getting away from the target and appearing as plasma spectral.

The electron temperature in the range of 1 eV– 2 eV is obtained for the iron plasma from the FeI line intensities while electron densities of the order of \( (6 \times 10^{19} - 8 \times 10^{19}) \) cm\(^{-3}\) are observed. Error percentage in this work was found to be between (0.04- 0.8).

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