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Optical Emission Spectroscopy Study of Fe Plasma at Atmospheric Pressure

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ABSTRACT

This paper studied spectroscopically Fe plasma produced by fundamental pulsed Nd-YAG laser with a pulse period of 5ns focused onto a rigid Fe target at atmospheric pressure. The plasma plume intensity, plume volume, temperature and density of electrons are calculated by spectroscopy of neutral atom and Fe ion line emission at different laser energy. The results show the Fe plasma plume intensity and plume volume increasing with increasing of Laser energy. The temperature of electron is calculated by using Boltzmann plot method while the electron density is determined by using Stark broadening method of measured spectral lines. The electron temperature was increasing with increasing of laser energy to become maximum at laser energy equal to 700mJ. If the laser energy increasing greater than 700 mJ, the electron temperature is reduced. In addition, the laser energy has no effect on the electron density.

KEYWORDS Laser-Induced Plasma , Optical Emission Spectroscopy, Fe plasma, plasma Plume.

Introduction:

Laser-induced plasma (LIPs) (sometimes called laser-produced plasma spectroscopy (LPPS)) of metals and alloys generated at laser pulse irradiances near the plasma ignition threshold are of great interest due to they have several important applications ,e .g. metal analysis in solid samples, thin film deposition and material processing [1]. Low-energy pulsed laser was used to generate plasma which vaporizes a small amount of the metal target in LIPs. LIPs is the better technique compare with the electric discharge due to cleanliness, large collection angle and high efficiency [2]. Measurements of the emission spectra lines revealed highly ionized plasma which expanded somewhat like a blast wave into the surrounding medium. Among the different plasma diagnostics techniques which are convenient tools for detecting various transient, optical emission spectroscopy (OES) has definite advantages pertaining to high temporal and spatial resolution without perturbation of LIPs [3].

In air and nitrogen the atmospheric pressure plasmas created by electrical discharges present considerable interest for a wide range of environmental, bio-medical and industrial applications (such as air pollution control, waste water cleaning, bio-decontamination and sterilization, material treatment, electromagnetic wave shielding, carbon beneficiation and nano tube growth) and element analysis. In addition to measurements of electrical discharge parameters and photo-documentation, optical emission spectroscopy (OES) gives valuable information on excited atomic and molecular states, enables to calculate the vibrational, rotational and electronic excitation temperatures of the plasma plume and thus the gas temperature, and sometimes even the electron temperature [4].

2. Experimental Setup:

Figure (1) illustrated the experimental set up for LIBs system. Pulse Nd-YAG laser with fundamental wave length 1064 nm and 5 ns pulse width was operated in this system.

The pulse Nd: Yag laser is focused on a Fe target that located in air at atmospheric pressure by using convex lens of focal length of 10 cm. Optical emission spectrometer (model THOR Lab) made in Germany was used as diagnostics tool to calculated the plasma parameers by diagnostics of the spatially integrated plasma light emissions. The spectrometer was placed at distance 10 cm from Fe target and at angle of 45^0 from laser beam direction. The results of spectrum of this system were calibrated with NIST data base software.

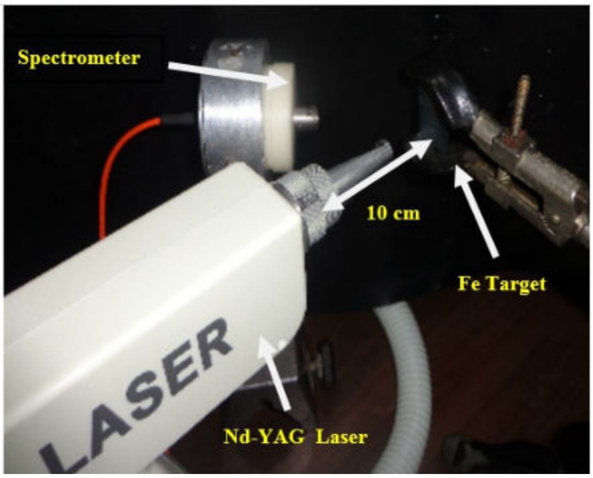


Figure (1): Experimental set up of LIBS system.

3. Measurement of Electron Temperature

For calculated the electron temperature (T_e), the most important spectroscopic techniques are the ratio of lines produced in sequential charge states of a single species. An accurate knowledge of the electron temperature causes to an understanding of the occurring plasma processes, namely dissociation, vaporization, excitation, ionization and transition probability. T_e can be calculated from the relative intensity of two or more optically lines having small separation in the emission wavelength and large separation in their upper excited states levels (which is named Boltzmann plot method) [5].

For plasma in local thermal equilibrium (LTE), the energy populations of the species are known by the Boltzmann distribution law [1]:

$$\frac{n_{k,Z}}{n_Z} = \frac{g_{k,Z}}{P_Z} exp\left(-\frac{E_{k,Z}}{k_B T_e}\right) \quad (1)$$

where the index z refers to the ionization stage of the species (where z=0 and 1 corresponding to the neutral and singly ionized atom, respectively), k_B is the Boltzmann constant, $n_{k,Z}$, $E_{k,Z}$ and $g_{k,Z}$ are the population, energy and degeneracy of the upper energy level k respectively, n_Z is the number density and P_Z is the partition function of the species in ionization stage Z. The integrated intensity I_z of a species in ionization stage Z in optically thin plasma is [1]:

$$I_Z = \frac{hc}{4\pi\lambda_{ki,Z}} A_{ki,Z} n_{k,Z} L \qquad (2)$$

where h, c, L, $A_{ki,Z}$ and $_{ki,Z}$ is the Planck constant, speed of light, the characteristic length of the plasma, the transition probability and is the transition line wavelength, respectively. By substituting equation (1) into equation (2) one obtained:

$$I_Z = \frac{hc}{4\pi\lambda_{ki,Z}} A_{ki,Z} L \frac{n_Z}{P_Z} g_{k,Z} exp\left(-\frac{E_{k,Z}}{k_B T_e}\right) \qquad (3)$$

Then, by taking the natural logarithm of equation (3), the equation (3) becomes[1,6,7]:

$$ln\left(\frac{I_Z\,\lambda_{ki,Z}}{g_{k,Z} A_{ki,Z}}\right) = -\frac{1}{k_B T_e} E_{k,Z} + ln\left(\frac{hcL_{nZ}}{4\pi P_Z}\right) \qquad (4)$$

Equation (4) yield a linear plot (which is called Boltzmann plot method) if one represents the magnitude on the left – hand side for several transitions against the energy of the upper level of the species in ionization stage Z. where T_e value can be determined from the slope of the Boltzmann plot method.

4. Measurement of Electron Density

The Stark broadening method of measured spectral lines was used for determining the electron density (n_e). In this method, the absolute intensities are not required, only the relative lines width and shape [^].

The present of electrons in the plasma can disturb the energy levels of the individual ions which broaden the emission lines originating from these excited levels. Stark broadening of well isolated lines in plasma is useful for determining the n_e provided that the coefficients of Stark-broadening have been calculated or measured.

The width of stark broadening spectral line depends on n_e. Both the linear and the quadratic stark effect are encountered in spectroscopy. The linear stark effect occurs only in the hydrogen atom and H-like ion. For the linear stark effect, n_e should be inferred from H line width from the formula [9]:

$$n_e = C(n_e, T)\Delta\lambda_{FWHM}^{3/2} \qquad (5)$$

The values of the parameter C (n_e, T) are listed in the literature [21], which determine the relative contribution of the electron collision on the electrostatic fields, and depend weakly on T and n_e.

On the other hand, For a non-H-like line the electron density (n_e) could be calculated from the Full Width at Half Maximum of the line from the equation [9,10]:

$$n_e = \left(\frac{\Delta\lambda_{FWHM}}{2\omega}\right) x10^{16} \qquad (6)$$

where ω is the electron impact width parameter (sometimes is called stark broadening parameter). The Stark width parameter (ω) of these lines and atomic data of the selected spectra lines is equal to $5.3 \times 10^{-3} nm$ and is taken from references [9,11].

5. Results and Discussions

5.1 Fe Plasma Plume and Typical Emission Spectrum

This section describes the experiment, used to produce plasma plume from solid Fe target. The emission spectrum lines detected and analysis the intensity of it to calculate the electron temperature and electron density at different laser energies. Figure (2) illustrated the photograph of the Fe plasma plume that produced by interaction of pulse Nd: YAG laser with Fe target at different laser energies.

It is clear from this figure; the Fe plasma plume intensity and volume are increases with increasing the laser energy. Figure (3) illustrated a typical spectrum of emission lines of the Fe plasma in the spectral range of 320-740 nm at different laser energies (600, 700, 800, 900 and 1000 mJ).

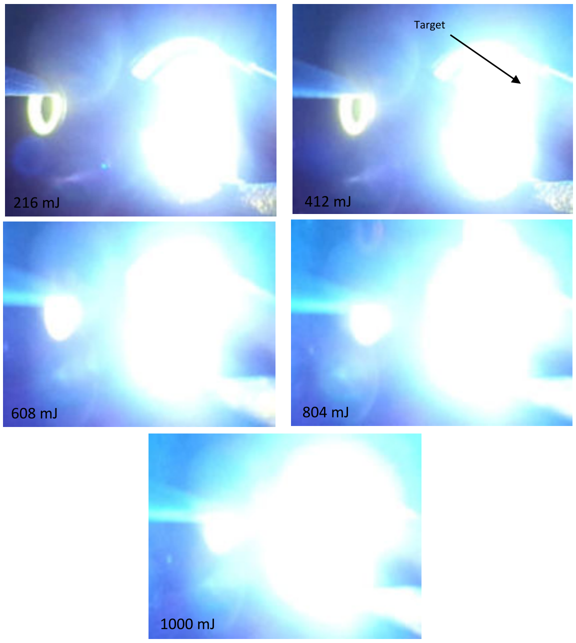
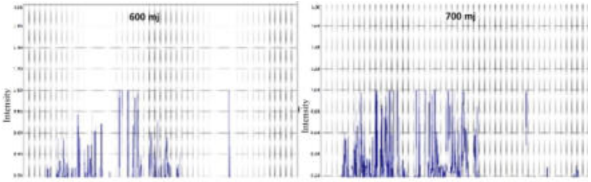


Figure (2):. Show the photograph the interaction of pulse Nd-YAG Laser with Fe target at different laser energy.



5.2 Effect of Laser Energy on Electron Temperature

The electron temperature (T_e) measurement for Fe plasma is developed from Boltzmann plot method by using several Fe I spectral lines at the different wavelengths and different laser energies (600,700, 800, 900 and 1000 mJ). Using equation (4) and plotting ln (Iλ / gA) versus E_k should yields a straight line with a slope equal to (–1/kT_e). The parameters of Fe I spectral lines are tabulated in table (1). These lines would be good candidates for calculating the electron temperature.

Table (1): Spectroscopic parameters of the Fe I lines [12].

Laser Energy= 600 mJ					
Spectrum	**Wavelength (nm)**	**$g_k A_{ki}$ (s^{-1})**	**E_i (eV)**	**E_k (eV)**	**Transitions**
Fe I	**354.20754**	**8.56E+08**	**2.8653912**	**6.3647**	$3d^6(^5D)4s4p(^3p^0) \rightarrow 3d^6(^5D)4s(^6D)4d$
Fe I	**355.66803**	**2.20E+07**	**2.8653912**	**6.3503485**	$3d^6(^5D)4s4p(^3p^0) \rightarrow 3d^6(^5D)4s(^6D)4d$
Fe I	**487.13179**	**1.22E+08**	**2.8653912**	**5.4099**	$3d^6(^5D)4s4p(^1p^0) \rightarrow 3d^6(^5D)4s(^6D)5s$
Fe I	**491.89937**	**1.25E+08**	**2.8653912**	**5.3852074**	$3d^6(^5D)4s4p(^3p^0) \rightarrow 3d^6(^5D)4s(^6D)5s$
Laser Energy= 700 mJ					
Fe I	**344.26688**	**1.22E+06**	**0.9581573**	**4.5585228**	$3d^7(^4F)4s \rightarrow 3d^6(^5D)4s4p(^1p^0)$
Fe I	**375.82327**	**4.44E+08**	**0.9581573**	**4.2562228**	$3d^7(^4F)4s \rightarrow 3d^7(^4F)4p$
Fe I	**383.42222**	**2.26E+08**	**0.9581573**	**4.1908608**	$3d^7(^4F)4s \rightarrow 3d^7(^4F)4p$
Fe I	**387.8018**	**5.40E+07**	**0.9581573**	**4.1543538**	$3d^7(^4F)4s \rightarrow 3d^7(^4F)4p$

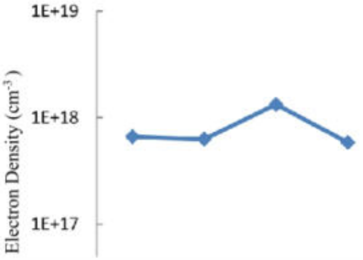
Laser Energy= 800 mJ					
Fe I	**361.97685**	**3.09e+06**	**2.4040744**	**5.8282951**	$3d^64s^2 \rightarrow 3d^6(^3H)4s4p(^3p^0)$
Fe I	**385.92123**	**7.98E+07**	**2.4040744**	**5.6158451**	$3d^64s^2 \rightarrow 3d^6(^3H)4s4p(^3p^0)$
Fe I	**649.498**	**8.43E+06**	**2.4040744**	**4.3124706**	$3d^64s^2 \rightarrow 3d^7(^4F)4p$
Laser Energy= 900 mJ					
Fe I	**384.04372**	**1.41E+08**	**0.9901111**	**4.2175832**	$3d^7(^4F)4s \rightarrow 3d^7(^4F)4p$
Fe I	**387.25009**	**5.25E+07**	**0.9901111**	**4.1908608**	$3d^7(^4F)4s \rightarrow 3d^7(^4F)4p$
Fe I	**417.39205**	**1.95E+05**	**0.9901111**	**3.9597236**	$3d^7(^4F)4s \rightarrow 3d^6(^5D)4s4p(^3p^0)$
Laser Energy= 1000 mJ					
Fe I	**375.82327**	**4.44E+08**	**0.9581573**	**4.256223**	$3d^7(^4F)4s \rightarrow 3d^7(^4F)4p$
Fe I	**383.42222**	**2.26E+08**	**0.9581573**	**4.190861**	$3d^7(^4F)4s \rightarrow 3d^7(^4F)4p$
Fe I	**387.8018**	**5.40E+07**	**0.9581573**	**4.1543538**	$3d^7(^4F)4s \rightarrow 3d^7(^4F)4p$

According to equation (4) and table (1), the variation of electron temperature with laser energy are calculated and plotted in figure (5).

One can observed from this figure, the electron temperature increases to become has a maximum value (1.79 eV) at energy equal to 700 mJ. This behavior is caused by the convert of thermal energy of laser to the kinetic energy of electrons because of increasing forward peaking with laser energy with constant laser spot size [13]. In addition, further increase of laser energy above 700 mJ causes to reduce the electron temperature. The reducing of Te with increasing of laser energy attributed to the increasing of electron collisions with the ambient gas. Therefore, T_e decreases with increasing of laser energy above 700 mJ.

5.3 Influence of Laser Energy on Electron Density

The electron density (n_e) is an important plasma parameter, crucial to the understanding of plasma characteristics and establishing equilibrium status. In this work, n_e was determination by the measuring of the broadening of a suitable emission line of Fe plasma spectrum. By using equation (6) after take the value of from references [9, 11], the effect of laser energy on the n_e was calculated and plotted in figure (5).



The results show the electron density was the same for all laser energies investigated. This result agrees with the results of the reference [14].

6. Conclusions

The laser induced breakdown spectroscopy technique has been applied as an analytical technique for the analysis of Fe plasma plume using the fundamental (1064 nm) Nd:YAG laser. Fe plasma plume intensity, plasma plume volume, The electron temperature and electron density of plasma plume are determined at different Nd:YAG laser energies. It is observed that the plasma plume intensity and volume are increases with increasing of the laser energy. The electron temperature increases to becomes have a maximum energy at laser energy 700mJ and then the electron temperature reduced when the laser energy greater than 700mJ. The effect of laser energy on the electron density shows that the electron density did not affected by increasing of laser energy.

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