Measurements of Plasma parameters in Laser-Induced Iron Plasma by Optical Emission Spectroscopy

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ABSTRACT

The iron plasma was produced via the interaction of high peak power laser with a solid iron plate in ambient gas (air).Experiments were performed to find out plasma properties for metal iron target which was irradiated by Q-switched Nd:YAG pulsed laser of energy(200- 500)mj, 532 nm wavelength and 9 ns pulse duration. Optical emission spectroscopy (300- 800 nm) has been used in studying the emission spectral lines of the generated plasma and calculating the electron temperature (Te), electron density (ne), Debye's length (λD), number of particles in Debye's sphere (ND) and plasma frequency (ωp). Plasma parameters were also studied as functions of laser energy.

Keywords: Iron plasma; plasma parameters; laser induce plasma, Optical emission spectroscopy.

1. INTRODUCTION

The interaction of strong electromagnetic radiation fields with the electrons in a condensed medium with a band gap larger than the photon energy can lead to the generation of quasi-free electrons in the conduction band through nonlinear processes such as multiphoton ionization or the tunnel effect [1].T hese free charges can subsequently gain sufficient kinetic energy from the electric field by inverse bremsstrahlung absorption to produce more carriers through impact ionization[2]. The rapid ionization of the medium leads to plasma formation. The characteristics of a plasma plume are dependent on the laser irradiance, laser wavelength, pulse duration, target composition and ambient[3-5].

Laser-induced plasma (LIP) techniques are used in chemical sensors as well as the detection of biological molecules. Other important applications of LIP include pulsed laser deposition, nanoparticle production and laser-induced breakdown spectroscopy [6]. Laser-induced breakdown spectroscopy (LIBS) has gained a great amount of interest in recent years. With LIBS, a pulsed laser is focused to vaporize and ionize a sample of material and when the laser irradiance exceeds the breakdown threshold of the material, aluminous plasma is created. By collecting the generated atomic emission from the laser-induced plasma, the elemental composition of the sample can be determined qualitatively and quantitatively [7-10].

The diagnostics of the plasma can be done through the measurements of the plasma electron density (ne) and temperature (Te). The electron density in general, specifies the state of thermodynamical equilibrium of the plasma, while the temperature determines the strength of the different distribution functions describing the plasma state[11]. Several diagnostic techniques like optical emission, absorption, fluorescence and resonance ionization spectroscopy are employed for the investigation of plasma[12-16]. The technique of the optical emission spectroscopy (OES) is non-invasive, easy to implement and with rapid measurements. Method of OES is based on recording light emitted from the plasma. Through collisions of plasma particles with electrons, plasma particles are excited to higher electronic states. Relaxation of excited particles to lower energy states is the origin of emitted photons of light.

In this paper we shall present the measurements of the plasma parameters (T_e, n_e, λ_D, ωp and N_D) during the interaction of the Nd:YAG laser at the fundamental wavelength of 532nm with iron target. The plasma parameters as a function of laser energy is studies. The variation in emission intensities from laser produced iron plasma with the laser energy in air is also discussed.

2. EXPERIMENTAL SETUP

The experimental setup used in order to diagnostics of laser induced iron plasma is described in figure (1).Q-switched Nd:YAG laser operating at the fundamental wavelength of 532 nm, pulse width of 9ns and repetition rate of 4 Hz was used for producing iron plasma in air. the laser beam was focused on a solid iron target placed in air ambient at atmospheric pressure using a lens of focal length of 10 cm, this provides a laser energy (200-500) mj form plasma over the target surface. The target was continuously rotated so that every laser pulse was incident on a fresh location of the target. The emission spectrum in the range (300-800 nm) of the laser induced iron plasma was recorded by an Ocean Optics (HR4000 CG-UV-NIR) spectrometer.

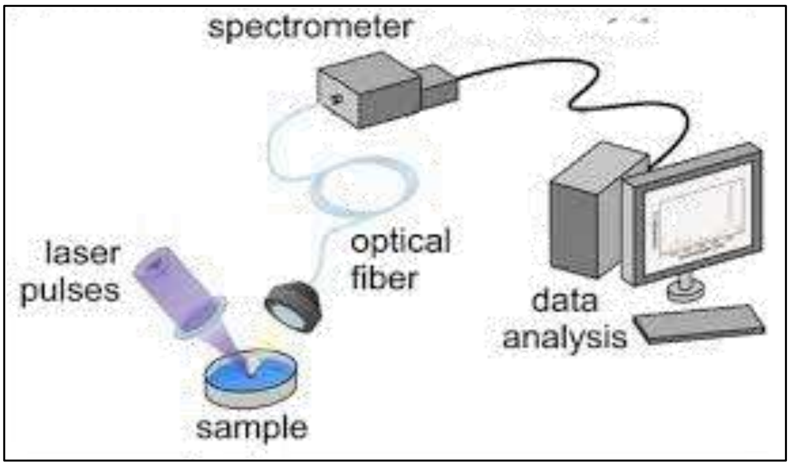

Fig.1: The experimental setup

3. RESULTS AND DISCUSSION

A. Emission Spectra Studies

The laser ablation process can be classified into three categories, evaporation of the target material, interaction of the evaporated cloud with incident laser beam resulting in cloud heating and plasma formation, and expansion and rapid cooling of the plasma. The optical emission spectrum of iron plasma confined in air ambient was recorded using OES technique. Figure (2) shows the emission spectrum in the spectral range 400-540 nm. The observed spectral lines of the laser-induced iron plasma emission are Fe I (at 410.87 nm), Fe I (at 423.72 nm), Fe I I (at 429.03 nm), Fe I (at 452.75 nm), Fe II (at 514.1 nm), Fe I (at 520.2 nm) and Fe II (at 529.4 nm). The transitions are identified using the spectral data base of National Institute of Standards and Technology (NIST) [17].

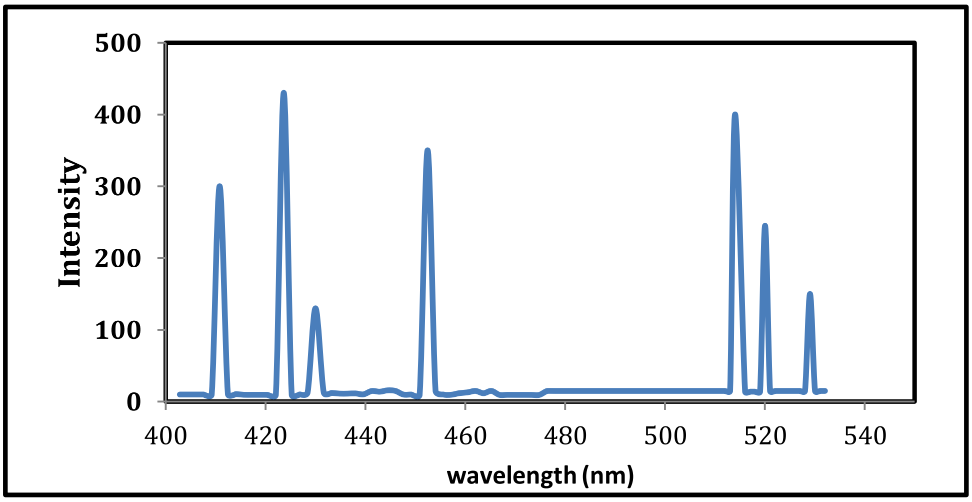

Fig.2: Optical emission spectrum of the Iron ablation plasma in air.

B. Plasma Parameters Calculation

Since the plasma generated under the present experimental conditions is in local thermodynamic equilibrium LTE, one can describe the plasma in LTE by a common temperature called the plasma temperature. By considering two spectral lines of the same species, characterized by different values of the upper level energy, the relative intensity ratio can be used to calculate the electron temperature as in equation (1).

$$T_e(E_1 - E_2)/K_B ln[\lambda_2 I_2 g_1 A_1/\lambda_1 I_1 g_2 A_2] \quad \ldots \quad (1)$$

where, A and g are the integrated line intensity (number of transitions per unit volume per unit time), transition probability and the statistical weight for the upper level, respectively.

For nanosecond laser induced iron plasma, the temperature was calculated from the ratio of the intensities of the two neutral iron lines for different laser energy. Figure (3) shows the relation between the electron temperature and the laser energy. Under the assumptions that the plasma is both in Local Thermodynamic equilibrium and optically thin, the lower limit of the electron density is given by McWhirter criterion:

$$n_e \geq 1.6 \times 10^{12}\, T^{1/2}\, \Delta E^3 \quad \ldots (2)$$

where, T (K) is the plasma temperature and ΔE (eV) is the energy difference between the states. The electron density of laser induced iron plasma was studied as a function of laser energy as shown in figure (4).

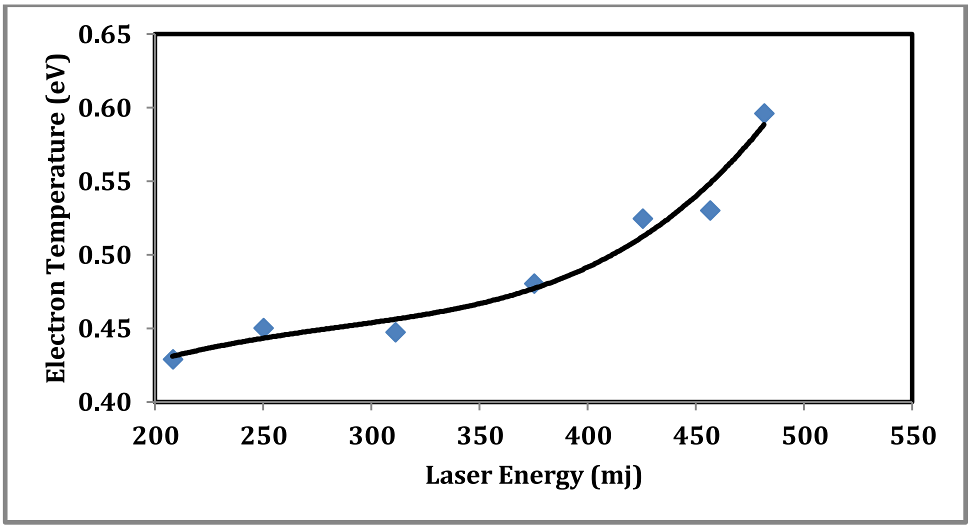

Fig 3: Variation of the plasma temperature of the plume with different laser energy

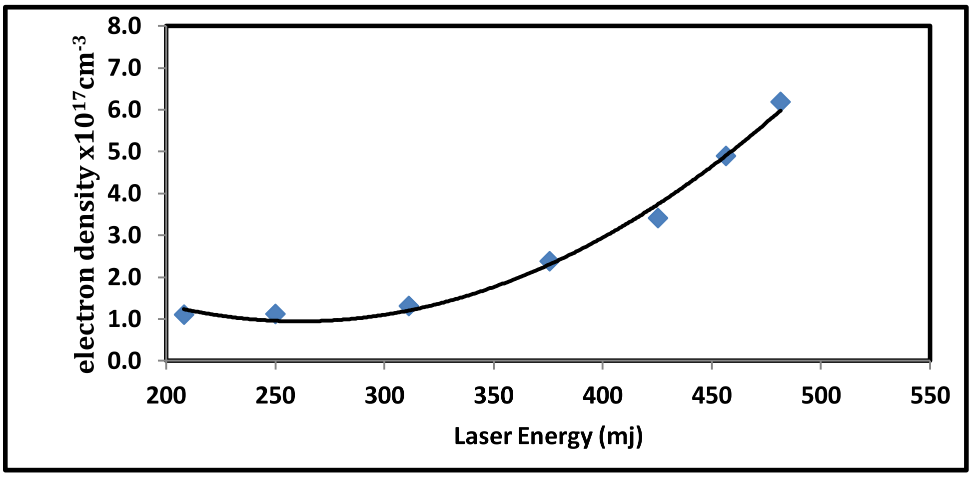

Fig 4: Variation of the electron density with different laser energy

From the figurers (3 and 4), at the lower irradiance levels, the mass ablation rate increases slowly with the increase in the laser irradiance. Hence, N_e and T_e are approximately constant. However, at higher irradiance, *N*e and T_e rapidly increase. The reason of this behavior is the increase in the laser peak power due to the absorption and/or refection of the laser photon by the plasma.

In laser induced plasma, Debye's length of plasma is given as:

$$\lambda_D = [\varepsilon_0 k_B T_e / e^2 n_e]^{1/2} \qquad \text{... (3)}$$

Number of particles in Debye's Sphere, in air as well as under vacuum is calculated by the formula:

$$N_D = 1.72 \times 10^9 \frac{T^{3/2}}{n^{1/2}} \qquad \text{... (4)}$$

where T_e is in eV and n_e in cm^{-3}. Plasma frequency can be calculated as:

$$\omega_p{}^2 = ne^2/\varepsilon_0 m \qquad \text{... (5)}$$

figures (5, 6 and 7) show the dependence of Debye's length (λ_D), plasma frequency (ωp) and number of particles in Debye's sphere (N_D) on the laser energy.

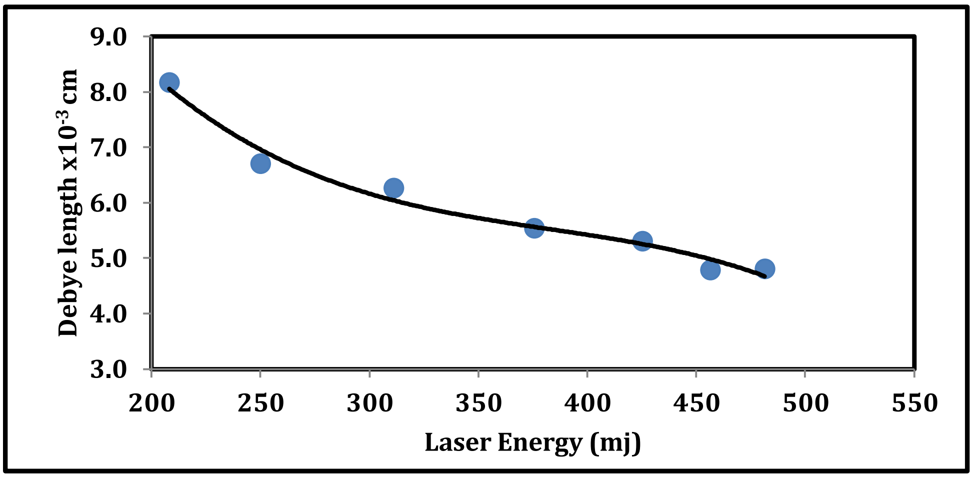

Fig. 5: Laser energy vs Debye's length.

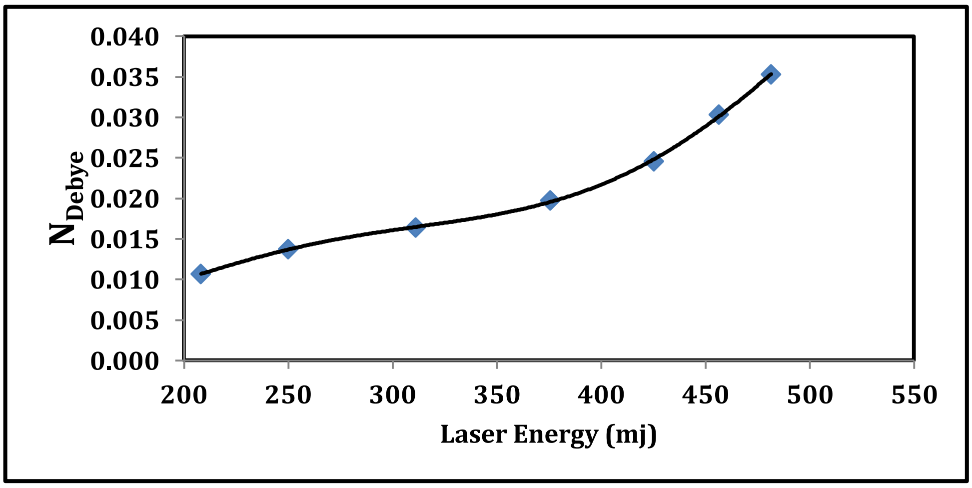

Fig. 6: Laser energy vs. number of particles in Debye's sphere.

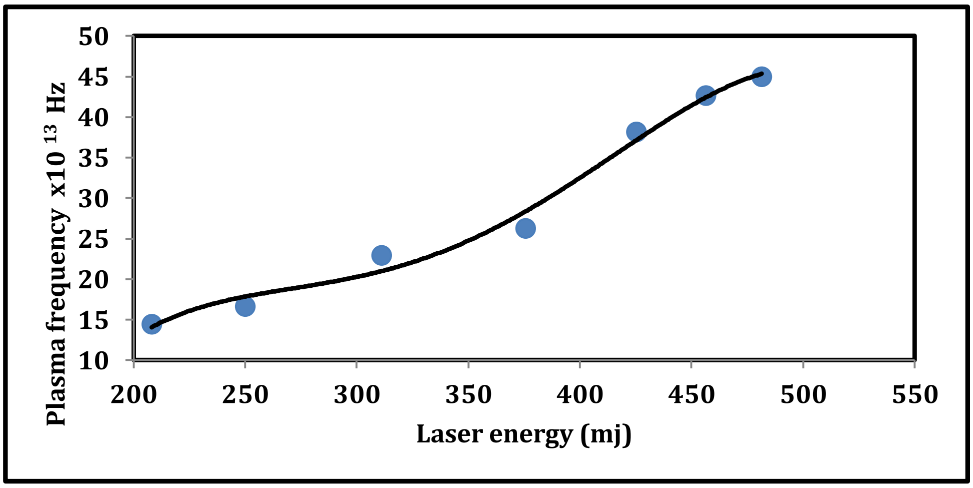

Fig. 7: Laser energy vs. plasma frequency.

From figure (5) there is decreasing in the value of Debye's length as the laser peak power increases. In laser induced iron plasma, the electrons gain less energy to overcome internal electric field which may be one of the reasons of decrease in Debye length at high laser energy. Figure (6) illustrates an interesting result that number of particles in Debye's sphere is found is a slow rise from 200 to 500 mj and there is a rapid increase in its value.

As the laser energy increases, the plasma frequency is approximately constant at the lower powers then there is an exponential increase in its values as shown in figure (7). The reason of this behavior is that the high laser energy produces comparatively more plasma emission as a result of more material ablation. Here the electron-ion collisions play an important role. In this case, the plasma frequency increases as a result of increasing electron density by increasing the absorption of laser in plasma through inverse Bremsstrahlung process.

4. CONCLISIONS

In this paper we studied by optical emission spectroscopy iron plasma obtained by laser ablation in air ambient. The emission lines from plasmas were measured and they were increased with increasing of the laser energy. The electron temperature was obtained for the copper plasma from the ratio intensities of two neutral lines. The value of the electron density (n_e), Debye's length (λ_D), number of particles in Debye's sphere (N_D) and plasma frequency (ωp) were measured.

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