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The application of magnetic field at low pressure for optimal laser-induced plasma spectroscopy

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ABSTRACT

The application of magnetic field in controlling the charged particles of the laser induced plasma is considered. The chara\cteristics of the plasma depend on the electron density and its recombination. The magnetic field effects as well as the ambient pressure are the key factors for determining the electron density of the plasma. Two different laser energies (Low: 30 mJ/pulse, High: 140 mJ/pulse) and the pressure range between 760 Torr and 10 Torr are used when focusing a Nd:YAG laser beam (1064 nm, 6 ns) onto the metal samples where the applied magnetic field varied between 0.1 and 0.5 Tesla. At 760 Torr, the plasma signal enhancement was obtained in the presence of magnetic field when the laser energy was low. With a lowered pressure however, the signal enhancement due to a magnetic field was achieved regardless of the laser energy. The enhancement of the signal in the presence of magnetic field is related to the electron density and the high frequency instability which are controlled by the ambient pressure and magnetic field intensity. In this paper, the optimal conditions for the laser-induced plasma spectroscopy in the magnetic field at various low pressures are discussed.

1. Introduction

Laser-induced plasma spectroscopy has been actively considered in the field of material science and chemical physics [1,2] where the controlling of the plasma is a pivotal technique that assures confidence in the detection. In the confinement of the plasma for signal enhancement, hot plasma is harder to confine over cold plasma because the hot plasma would be easily quenched by a direct contact with the ordinary confining walls [3]. Instead, hot plasma may be better confined magnetically wherein the plasma characteristics when magnetically confined have proven useful in areas of astrophysics and solar physics [3]. The laser-induced plasma usually grows and expands into the surrounding [4], while the growth and expansion stop in the presence of a magnetic field. This is because the charged particles subjected to a magnetic force execute a helical orbit about an axis parallel to the direction of a magnetic field, and also the gyroradius of the particle decreases as the strength of the field increases. This means that the kinetic energy of plasma becomes equal to the displaced magnetic energy [5]. The particle dynamics of plasma is governed by the internal fields and the motions of the particles themselves, as well as by the externally applied fields. Due to the long range of electromagnetic forces, each charged particle in the plasma interacts simultaneously with a considerable number of other charged particles, resulting in the collective effects that are responsible for the wealth of physical phenomenon that takes place within the plasma [6]. In any means, the magnetic confinement causes not only the conversion of a kinetic energy of the plasma into a thermal energy [7,8], but also the increase of both effective density and the rate of electron recombination in the plasma [6,9,10]. Therefore, the collective effects of these phenomena are expected to enhance significantly the emission intensity during the laser-induced plasma spectroscopy [11,12].

The magnetic field effects on the plasma emissions as previously reported in the literature were based under atmospheric-pressure condition with a single or limited range of magnetic intensities. Various magnetic confinement techniques that have been introduced for plasma emission enhancement use the oblique incidence of the laser on sample surfaces [13], double-pulse excitation [14–16], low pressures [17], and purge gas [18]. In this paper, we have devised an experimental setup aimed at understanding the combined effect of the magnetic field and the very low pressures. A significant improvement to a magnetically confined plasma emission is reported.

2. Experimental setup

The pulsed Nd:YAG laser (Surelite I, 1064 nm, 6 ns) was focused on the metal surfaces (Ti, Cu, Zn) of 3 mm × 3 mm × 1 mm using a BK-7 convex lens of 90 mm focal length. Every metal sample has a purity of 99.99%. Two laser energies of 30 mJ/pulse and 140 mJ/pulse are used for low and high energy cases, respectively. The spot diameter of the focused beam is 0.7 mm, as such the irradiances are 1.3 GW/cm^2 and

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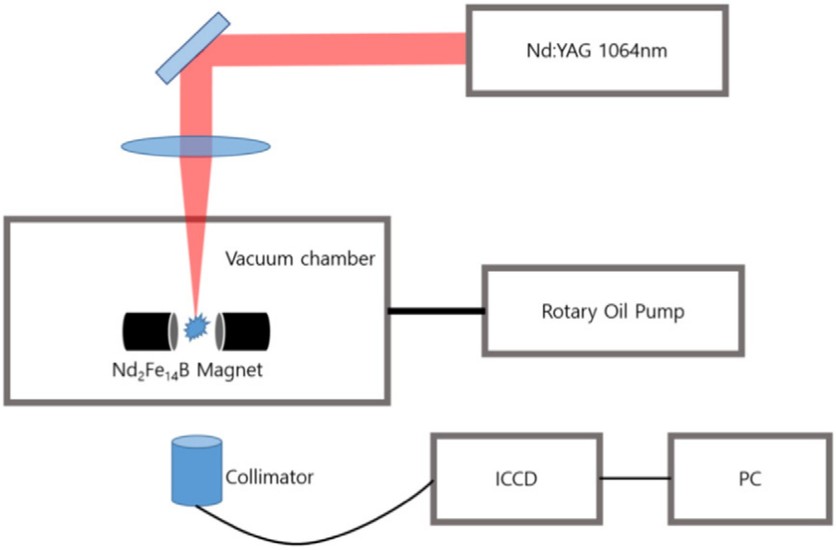

Fig. 1. Schematic view of the experiment.

6.1 GW/cm^2 for laser energy of 30 mJ and 140 mJ, respectively. The permanent magnetic field of $Nd_2Fe_{14}B$ magnet was used in the confinement of the laser-induced plasma. One piece of a magnet has a cylindrical shape of 10 mm in diameter and 5 mm in height. The magnetic field intensity was measured by Gauss-meter (AlphaLab Inc. GM1-ST) which has the measurement range of ± 2 T and resolution of 0.1 G, and it was measured at the center of the two magnets where the samples were located during the experiment. One pole of the magnet faced the other, which gave 0.1–0.5 T permanent magnetic field with a gap distance being controllable. The spectra of laser-induced plasma were obtained with the spectrograph (Andor Mechelle ME5000 Echelle), the ICCD (Andor iStar DH734-18F-03), and the collimator (Andor ME-OPT-0007). The gate-width is 20 μs regardless of experimental conditions, but the gate-delay of ICCD is varied from 1 μs to 0.1 μs, in order to obtain optimal signal to noise ratio for each pressure condition. The spectral resolution ($\lambda/\Delta\lambda$) of spectrometer is above 6000, and the spectral range is 200–975 nm. The spectrograph was synchronized with the laser beam, using the pulse generator (BNC 565-8CG) and the oscilloscope (Tektronix TDS-2014), shown in Fig. 1.

It is known from the previously investigations that plasma generation is influenced by the laser parameters (intensity, pulse duration, and wavelength) [10–22], the physical properties of target material (ionization potential, reflectivity and thermal conductivity), and the ambient conditions [23]. In the present experiment, three parameters namely laser energy, magnetic field intensity, and ambient pressure were varied while all other parameters are fixed. Fig. 2 shows a picture of the plasma in the presence of the magnetic field.

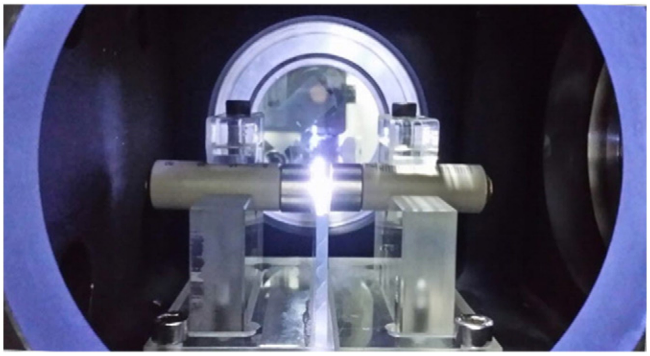

Fig. 2. Vacuum chamber and the laser-induced plasma in the presence of a magnetic field.

To control the position and angle of the magnet pair precisely, a holder is designed and installed inside the chamber. The metal samples are placed at the center of the magnets while the magnetic intensity is controlled by changing the gap between the magnets. The dimension of the vacuum chamber is 200 mm × 200 mm × 200 mm in which depressurization is achieved via the rotary oil pump (EHP 600). The data were obtained from 10 shot laser ablations, and the first 5 shots were discarded to prevent any surficial contamination. As a result, it is an arithmetic mean of the remaining 5 shots.

3. Results and discussion

The relationship between the emission intensity and the magnetic field intensity is written as follows [23],

$$\frac{I_1}{I_2} = \left(1-\frac{1}{\beta}\right)^{-\frac{3}{2}}\left(\frac{t_1}{t_2}\right)^3 \tag{1}$$

where β is $8\pi nkT_e/B^2$ with k being Boltzmann constant, B being intensity of the magnetic field and n, T_e being electron density and temperature, respectively. Consequently β is a ratio between plasma pressure and magnetic pressure. I is a signal intensity, and subscripts 1 and 2 represent with and without the magnetic field, respectively. t is the expansion time for each case. As β approaches 1, plasma particles stop at some location and make circular movement and the emission intensity becomes large. There are additional factors such as resistivity or interaction with ambient gas that would prohibit the plasma to stop [19]. Thus Eq. (1) holds well if plasma is a fully conducting medium with no ambient gas [24]. Nevertheless it is reasonable to assume Eq. (1) for the relationship between the intensity and the magnetic field in the present investigation.

When $\beta \gg 1$, the expansion of the plasma occurs rather fast and smoothly. Otherwise (strong magnetic pressure), plasma expansion is slow and the intensity of the emission increases under the confinement condition. To understand this relationship between signal intensity and magnetic field, we consider varying the magnetic fields while fixing pressure (760 Torr) and laser energy (30 mJ).

Fig. 3 shows the emission spectra of Ti II (368.5 nm) with varying magnetic fields at 0.2 T increment. For this low energy case (30 mJ), the signal intensity at 0.5 T showed a noticeable increase, suggesting that magnetic pressure approaches plasma pressure, which is consistent