20PA-033

Spectroscopic study of laser produced Fe plasma for electron temperature and density measurements
可視分光によるレーザー生成鉄プラズマの電子温度･密度計測

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In order to understand laser-ablation dynamics of iron, we measured spatiotemporal visible emissions of Fe I transition and derived the plasma parameters. Immediately after laser-irradiation, continuum spectra following black body radiation were observed, by which we estimated radiation temperature. After that, line spectra being in local thermal equilibrium appeared, and we determined electron temperature from the Boltzmann plot of high-lying levels. On the other hand, prominent line broadening due to the Stark effect was observed, from which the spatial variation of electron density was derived.

1. Introduction

Study of laser-ablation using metal targets has been widely conducted for the purpose of laser induced breakdown spectroscopy (LIBS). On the other hand, demand for laser-processing even in nanometer domain is growing, since laser-processing has advantage of suppression of heat damage on the substance subjected to intense lasers. Furthermore, the laser-ablation is also utilized as a method for ablating radiation contaminated surface.

Iron is one of the most widely used materials, and the understanding of laser-ablation processes, which laser-solid interaction, phase-change, laser-plasma interaction and more processes are intricately related [1], is important.

To this end, we investigated the ablation dynamics of laser-produced iron plasmas which were generated by a high-intensity Nd:YAG laser pulse. Spatiotemporal visible emission spectra were observed. Analysis of the intensity distributions and spectral profiles revealed characteristics of the plasma density and temperature with high spatial and temporal resolutions.

2. Experimental Setup

The experimental setup is shown in Figure 1. We used a Q-switched Nd:YAG pulsed laser having a pulse duration of ~5 ns and 10 Hz reputation rate, which was capable of delivering 1.25 J at its fundamental frequency (1,064 nm). The laser energy was varied by using a variable laser beam attenuator (Metrolux). The laser beam was focused onto the target surface using a lens of *f*=300 mm, and maximum laser intensity was ~1×10^{14} W/cm^2. The target was 0.20 mm-thick iron slab and was mounted on a two-dimensional stage to provide a flesh surface on the beam spot. Visible radiation emitted from the laser plasma (wavelength region: 400 to 700 nm) was measured by a spectrometer (Acton SpectraPro, focal length: 0.50 m, grating: 1200-line/mm). The dispersed light was detected by an image intensified charge-coupled device (ICCD, Princeton Instrument, PI-MAX). An optical bundle fiber (48 cores) and achromatic lenses (*f*=100 and 150 mm) were used to transmit and focus the emission on the entrance slit. Spatial resolution was around 0.012 mm and the gate width of the CCD camera was 200 ns.

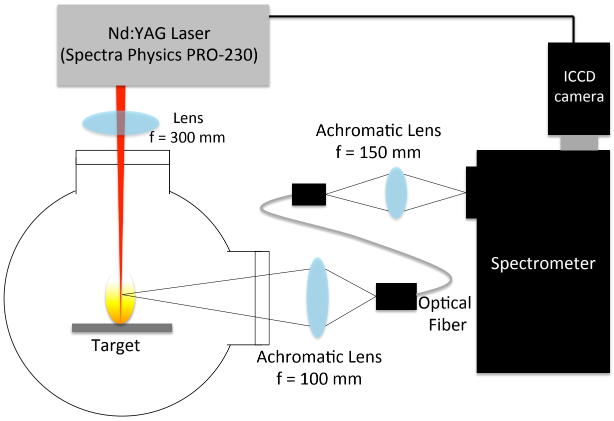

Fig.1 Experimental Setup of laser-ablation

3. Results and Discussion

CCD images are accumulated with 100 laser shots, for the CCD gate time window of 200 ns. In the time window of 0-0.2 μs, the continuum spectrum was observed, which is caused by black body radiation. Therefore, continuum emission in the visible and infra-red wavelengths could be fitted to Planckian curve, yielding the radiation temperature in the initial laser-ablation phase [2]. After vanishing continuum, distinct line emissions attributed to Fe I transitions appeared.

Figure 2 shows the spectrum attributed to Fe I $3d^7(^4F)4p$-$3d^7(^4F)4d$ transition (538.34 nm) [3].

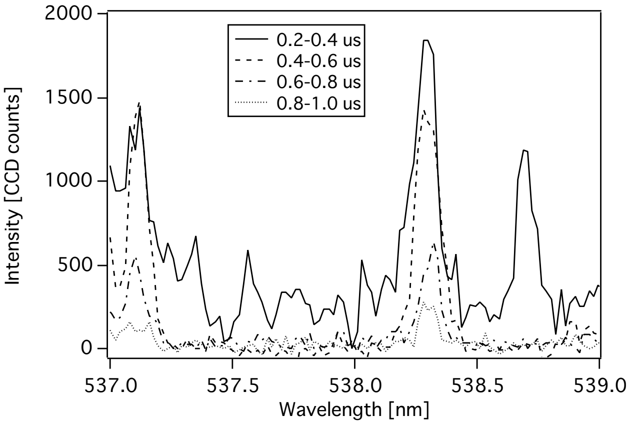

Fig.2 Fe I 538.34 nm emission for various time delays

There are two major reasons for line broadening, i.e., Doppler broadening due to the finite temperature of the emitting atoms and Stark broadening due to encountering with charged particles [4]. Freudenstein and Cooper (1979) gives experimental value for the relationship between the normalized full width at half maximum (FWHM) of the Stark broadened lines w_e and the electron density n_e for 538.3 nm Fe I line [5], i.e.

$$\frac{w_e}{n_e} = 0.097 \pm 0.004(10^{-16}\,\text{Å}\,\text{cm}^3).$$

Figure 3 shows (a) the space distribution of electron density in the time window of 0.4-0.6 μs (b) temporal evolution at the position of 0.61 mm. The maximum of the spatial distribution is obtained in the surface of the target, and the electron density was decrease with distance from the target. Behind 4 mm from the target, no line spectrum was observed. In the time window of 0.6-0.8 μs, the electron density was half the value in the gate time of 0.2-0.4 μs and the electron density decline became slowly.

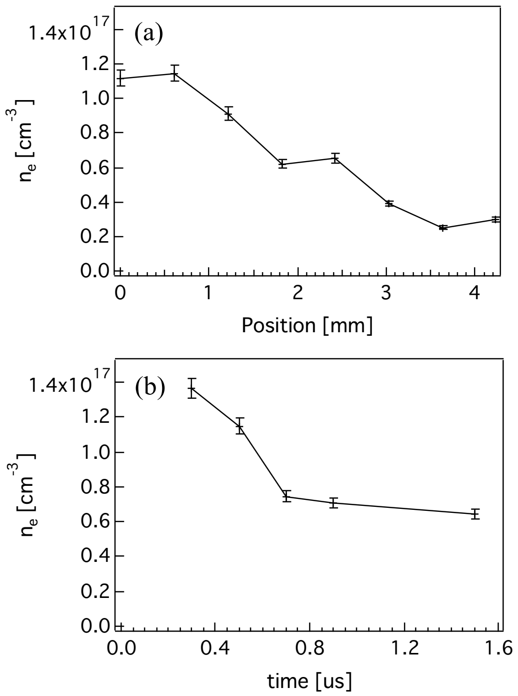

Fig.3 (a) Spatial and (b) temporal distributions of the electron density

6. Conclusion

In order to investigate the ablation dynamics of laser-produced iron plasma, which were generated high-intensity Nd:YAG laser, we measured visible radiation emitted from iron plasmas. Continuum emission was observed in the time window of 0-0.2 μs, which can be explained by black body radiation. After continuum disappeared, distinct line emissions attributed to Fe I transition were observed. Electron density was estimated from the Stark broadening. The maximum of the spatial distribution is obtained in the surface of the target, and the electron density was decrease with distance from the target. After the time window of 0.4-0.6 μs, the electron density was half the value in the gate time of 0.2-0.4 μs.

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