Wideband High-Resolution Spectroscopy on Al-pellet Ablation Plasmas in Large Helical Device

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Abstract. An aluminum pellet has been injected into a high-temperature plasma produced in the Large Helical Device (LHD). Emission from an ablation cloud of the pellet in a whole visible range is simultaneously measured with an echelle spectrometer having an instrumental resolution from 0.055 nm at 400 nm to 0.10 nm at 750 nm. More than 50 of Al I, II, III and IV lines are resolved. We estimate the electron temperature and density of the ablation cloud from the intensity distribution and Stark broadening of the emission lines, respectively. The electron temperature and density are found to show increase and decrease, respectively, as an increase in the charge state of aluminum. We also determine the Stark broadening coefficients of several Al II lines from the observed Stark widths.

1. Introduction
Pellets containing various elements have been injected into a magnetically confined fusion plasma for the purposes of impurity transport study and disruption control of the plasma [1,2]. In the Large Helical Device (LHD), for example, pellets of carbon, aluminum, titanium and so on were injected to examine the dependence of transport coefficients on the impurity nuclear charge [2].

A pellet plunged into the plasma is immediately ablated due to heat flux from the plasma. A high density plasma called ablation cloud forms in the vicinity of the pellet, which emits many atomic and ionic emissions. From spectroscopic studies of the emissions, not only impurity transport in the main plasma, but also ablation mechanism, atomic processes in the ablation cloud, and acquisition of atomic data like line-broadening coefficients can be done. Wideband spectra containing many emission lines have been measured for hydrogen, carbon and aluminum pellets [3,4,5]. From such measurements, the population distribution of excited levels of atoms or ions in the ablation cloud has been investigated and plasma parameters such as electron temperature, neutral atom density and ion density have been estimated. On the other hand, high resolution spectra of the emission lines have been measured for carbon pellets, and the electron density of the cloud has been estimated from the Stark broadening [4].

In this work, we use an echelle spectrometer to perform wideband and high-resolution spectroscopic measurements at one time for a single ablation cloud.

2. Experimental setup
The LHD has a torus-shape vacuum vessel with a major radius of about 3.9 m and a minor radius of about 1 m, in which a plasma of about 30 m³ is confined. The plasma is heated by electron cyclotron heating, ion cyclotron resonance heating and neutral beam injection. Major radius position of the magnetic axis is 3.90 m and the field strength at the magnetic axis is 2.54 T (shot number: 104159).
We use a pure aluminum pellet having a cylindrical shape whose diameter and length are 0.8 mm. The pellet is accelerated in a 6 m long acceleration tube with a pneumatic pipe-gun system, which uses helium gas of 18 atm pressure, and then injected horizontally into the plasma from an outer port of the LHD (1-O port). Figure 1 shows a schematic illustration for a part of the equatorial plane of the LHD, in which the pellet trajectory is indicated by the thick arrow.

We place a lens having a focal length of 10 mm and an optical fiber having a core diameter of 1 mm at an observation port close to the pellet acceleration tube. The line of sight is parallel to the injection direction of the pellet as shown in figure 1. Emission from the pellet ablation cloud generated in the LHD plasma is recorded by a CCD camera (Andor, DV435-BV, 1024×1024 pixels) through an echelle spectrometer we developed. Since the exposure time of CCD is set to be 95 ms, which is much longer than the period of luminous radiation from the ablation cloud of several ms, the entire emission during the pellet ablation is accumulated in a single measurement. The CCD is cooled to be -25°C to reduce thermal noise.

For the purpose of the wavelength calibration and resolution estimation of the echelle spectrometer, we measure emission lines of a Th-Ar hollow cathode lamp (Heraeus, P858A) because it has many emission lines in the visible region and the line widths are small enough. It is found that the instrumental function of the spectrometer can be approximated by a Gaussian profile. We evaluate the instrumental width (FWHM) by fitting with a Gaussian function at the entrance slit width of 25 μm as a function of the wavelength. Typical instrumental widths range from 0.055 nm at 400 nm to 0.10 nm at 750 nm. We also calibrate the relative sensitivity of the spectrometer for the whole wavelength region using a tungsten standard lamp with an integrating sphere (Labsphere, USS-600C).

3. Results and discussion

The observed spectrum is shown in figure 2. It is noted that the intensity is shown in a logarithmic scale. More than 100 emission lines are resolved, in which more than 50 of Al I, Al II, Al III and Al IV lines are identified with available databases [6,7]. The identified lines are indicated in figure 2 by arrows. The lines denoted by ‘a’-‘d’ are used to estimate electron density of the ablation cloud from their Stark widths as explained below. Since the LHD plasma contains hydrogen, helium, argon, etc, emission lines of these elements are also seen in figure 2.

Many of observed lines are found to show broadenings, which cannot be reproduced by a Gaussian profile. The broadenings may be mainly due to Stark broadening having a Lorentzian profile because electron density in the ablation cloud is expected to be high. Furthermore, influence of the Zeeman splitting on the line profile may not be negligible. We fit the observed line profiles as follows; we
calculate the splitting and relative emission intensities of the Zeeman components with the method based on the perturbation theory for \( B = 1.5 \) T, which is the approximate magnetic field strength at the location where the radiation intensity of the ablation cloud takes its maximum, and then fit the entire line profile by a sum of several shifted Voigt functions according to the Zeeman splitting, which have a common Lorentz width, \( W_L \), and a fixed Gaussian width, \( W_G \), determined previously as the instrumental width. The adjustable parameters for the fit are \( W_L \) and the area of the spectrum. A typical example of the observed spectrum and the result of the fit is shown in figure 3.

![Figure 2. Observed spectrum of the aluminum pellet ablation cloud.](image)

![Figure 3. Enlarged spectrum of the line denoted by ‘a’ in figure 2. The fitted result is shown by the red curve. The vertical bars show the Zeeman splitting and the intensities of the Zeeman components.](image)

Emission line intensity is given as the area of the spectrum. The line intensity, \( I(p,q) \), from a level \( p \) to a level \( q \) is proportional to the upper level population, \( n(p) \), as

\[
I(p,q) = h \nu(p,q) A(p,q) n(p)
\]

(1)

where \( h \) is Planck’s constant. \( \nu(p,q) \) and \( A(p,q) \) are the frequency of light and the spontaneous transition probability, respectively.

Populations of excited levels of atom and ions in the ablation cloud can be estimated from the observed line intensities with equation (1) for well-resolved emission lines enough to evaluate area of the spectra with available transition probabilities [6,7]. The results for neutral aluminum atoms (Al), singly-ionized aluminum ions (Al\(^+\)) and doubly-ionized aluminum ions (Al\(^{2+}\)) are shown in figure 4 by the Boltzmann plot against the upper level energy. The population distribution seems to be on a straight line for each charge state.

It is known that in a case where atoms or ions of an excited level \( p \) in a plasma is in thermo dynamic equilibrium (LTE), population in the level \( p \) follows the Saha-Boltzmann distribution;

\[
\frac{n_z(p)}{g_z(p)} = \frac{1}{2} \left( \frac{\hbar}{2\pi mkT_e} \right)^{1/2} \exp \left( \frac{\chi_z(p)}{kT_e} \right) \frac{n_{2z+1}(1)}{g_{2z+1}(1)}
\]

(2)

where \( m \) is the electron mass, \( k \) is the Boltzmann constant. \( n_A(p), g_A(p) \) and \( \chi_A(p) \) are the population, statistical weight and ionization potential of the level \( p \), respectively, of a charge state \( \text{Al}^{2+} \) [8].
stands for the ground state level. $n_e$ and $T_e$ are the electron density and temperature, respectively. In this case, the Boltzmann plot of the upper level populations is on a straight line, the slope of which is determined by the electron temperature. From the straight lines fitted to the population distributions as shown in figure 4, we estimate $T_e$ of the ablation cloud for Al, Al$^+$ and Al$^{2+}$ plasmas (more strictly, in the region of ablation cloud where most of Al atoms, Al$^+$ ions or Al$^{2+}$ ions are emitting), the values of which are shown in figure 4.

**Figure 4.** Boltzmann plot of upper level populations for (a) Al, (b) Al$^+$ and (c) Al$^{2+}$ plasmas.

Regarding the Lorentz width, the natural broadening determined by the spontaneous transition is negligibly small in comparison with the observed width. Therefore, we treat the observed Lorentz width as the Stark width; $W_S = W_L$. The Stark width is proportional to the electron density as

$$W_S = C_S(T_e)n_e$$

(3)

where $C_S$ is the Stark broadening coefficient.

$W_S$ of the Al II lines denoted by ‘a’, ‘b’, ‘c’ and ‘d’ in figure 2 have been determined in previous calculations and experiments at several $T_e$ as shown in figure 5 [9,10,11]. The curves in the figure are the results of the fit with exponential functions. From the curves and $n_e$ in previous calculations and experiments, we determine $C_S$ of the lines at $T_e = 1.51$ eV, which is the temperature of the Al$^+$ plasma. Since the experimental data only at $T_e = 0.9$ eV is available for the Al II line denoted by ‘b’, we adopt the value of $C_S$ at $T_e = 0.9$ eV as that at $T_e = 1.51$ eV assuming $T_e$ dependence of $C_S$ is small in this temperature region. The estimate $n_e$ from these lines are listed in table 1. It is found that scatter of the values are within 15 % of the average. We adopt the average value as the electron density of the Al$^+$ plasma.

**Figure 5.** Stark widths of the Al II lines [9,10,11], which are denoted by ‘a’, ‘b’, ‘c’ and ‘d’ in figure 2. The curves are the fitted result by exponential functions.
Table 1. Electron densities estimated from the Stark widths of the Al II lines denoted by ‘a’, ‘b’, ‘c’ and ‘d’ in figure 2.

| $\lambda$ (nm) | Transition (lower - upper) | $C_S$ (nm m$^3$) | $W_S$ (nm) | $n_e$ (m$^{-3}$) |
|----------------|----------------------------|------------------|------------|-----------------|
| a 466          | 3p$^2$(1D) - 3s4p(1P)      | 1.01×10$^{-24}$  | 0.042      | 4.1×10$^{22}$   |
| b 559          | 3s4p(1P) - 3s4d(1D)        | 3.8×10$^{-24}$   | 0.182      | 4.8×10$^{22}$   |
| c 624          | 3s4p(1P) - 3s4d(2D)        | 3.58×10$^{-24}$  | 0.172      | 4.80×10$^{22}$  |
| d 684          | 3s4p(1P) - 3s5s(1S)        | 3.30×10$^{-24}$  | 0.165      | 5.01×10$^{22}$  |
| avg            |                           | 4.7×10$^{22}$    |            |                 |

Similar analyses can be done for the Al I and Al III lines. In table 2, we summarize $T_e$ and $n_e$ of the ablation cloud for Al, Al$^+$ and Al$^{2+}$ plasmas. It is found that $T_e$ increases while $n_e$ decreases as an increase in the charge state. This tendency suggests that aluminum in different charge states emits radiation in different regions of the ablation cloud and/or at different time during the ablation. It has been reported, however, that intensity ratios of emission lines of various carbon ions change little during the carbon pellet ablation [4]. Supposing that the ablation mechanism due to heat flux from the LHD main plasma is the same for carbon and aluminum pellets, we attribute the observed tendency to an inhomogeneous structure of the ablation cloud; the plasma region for neutral atoms is close to ablating pellet where $n_e$ is high and $T_e$ is low and the region for a higher charge state is farther from the pellet where the cloud is expanding in the LHD main plasma with increasing $T_e$ and decreasing $n_e$.

Table 2. Electron temperatures and densities estimated from the observed emission lines of aluminum atoms and ions.

|          | $T_e$ (eV) | $n_e$ (m$^{-3}$) |
|----------|-----------|-----------------|
| Al (Al I)| 0.49±0.04 | 3.0×10$^{23}$   |
| Al$^+$ (Al II)| 1.5±0.04 | 4.7×10$^{22}$   |
| Al$^{2+}$ (Al III)| 2.5±0.2 | 3.6×10$^{22}$   |

From the observed Stark widths with $n_e$ estimated above, we determine Stark broadening coefficients of several Al II lines, the values of which have not been reported. The determined values are listed in table 3 together with the data used for the $n_e$ estimation. It is demonstrated that the ablation plasma spectroscopy with a simultaneous wideband and high-resolution measurement can be a powerful tool to determine Stark broadening coefficients.

Table 3. Stark broadening coefficients of Al II lines (at $T_e=1.5$ eV).

| $\lambda$ (nm) | Transition (lower - upper) | $W_S$ (nm) | $C_S$ (nm m$^3$) |
|----------------|----------------------------|------------|-----------------|
| This work      | Previous studies           |            |
| 463            | 3s5s(1S) - 3s8p(1P)        | 0.051      | 1.1×10$^{-24}$  |
| 465            | 3s4d(1D) - 3s9f(1F)        | 0.031      | 6.6×10$^{-25}$  |
| 466            | 3p$^2$(1D) - 3s4p(1P)      | 0.042      | 8.9×10$^{-25}$  |
| 559            | 3s4p(1P) - 3s4d(1D)        | 0.182      | 3.9×10$^{-24}$  |
| 624            | 3s4p(1P) - 3s4d(2D)        | 0.172      | 3.7×10$^{-24}$  |
| 634            | 3s3d(1D) - 3s5p(1P)        | 0.265      | 5.7×10$^{-24}$  |
| 683            | 3s4p(1P) - 3s5s(1S)        | 0.165      | 3.5×10$^{-24}$  |
| 705            | 3s4s(1S) - 3s4p(1P)        | 0.077      | 1.7×10$^{-24}$  |
| 747            | 3s3d(1D) - 3s4f(1F)        | 0.188      | 4.0×10$^{-24}$  |
4. Conclusion
We simultaneously observed emission spectrum of an ablation cloud of an aluminum pellet injected into an LHD plasma in the entire visible region with high-resolution. More than 50 of Al I, II, III and IV emission lines were resolved in the spectrum. Population distributions of excited levels of atoms and ions in the Al, Al I and Al II plasmas converted from the observed line intensities were analyzed. LTE states were thought to be generated in the Al, Al I and Al II plasmas and the electron temperatures of the plasmas were estimated. The electron densities of the plasmas were also estimated from the observed Stark widths by comparison with the previously reported Stark widths. It was found that the electron temperature and density increases and decreases, respectively, as an increase in the charge state of aluminum. The phenomenon implies a laminar structure of the ablation cloud; higher density, lower temperature and lower ionized plasma inside and lower density, higher temperature and higher ionized plasma outside. On the other hand, Stark broadening coefficients of several Al II lines were newly determined from the observed Stark width with the estimated electron density.

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