Estimation of sheath electric field based on Dopper broadened absorption spectrum of hydrogen Balmer-α line

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The measurement of sheath electric field is still an important issue in plasma physics. In this work, we examined the applicability of the Doppler-broadened absorption spectrum of the hydrogen Balmer-α line to the estimation of the sheath electric field [1]. Measuring the absorption spectrum of the hydrogen Balmer-α line using a tunable single-mode diode laser is not too difficult. In addition, since the cost for the experimental setup is also relatively small, laser absorption spectroscopy at the hydrogen Balmer-α line is useful for the measurement of the sheath electric field, even though the detection limit is intermediate in various methods developed to date.

The experiment was carried out in inductively coupled hydrogen plasmas at a pressure of 47 mTorr. A one-turn rf antenna was inserted into a vacuum chamber, and it was connected to an rf power supply at 13.56 MHz via a matching circuit. The rf antenna was electrically insulated from the plasma by covering its surface with glass fibers. The rf power was pulse modulated at a frequency of 20 kHz to amplify the absorption signal using a lock-in amplifier. The instantaneous rf power and the duty factor were 1 kW and 50%, respectively. A planar electrode which was connected to a dc power supply was inserted into the vacuum chamber from the opposite side to the rf antenna. A linearly-polarized, single-mode diode laser beam was injected into the plasma. The wavelength of the diode laser was scanned around the Balmer-α line of atomic hydrogen. The distance between the diode laser beam and the surface of the planar electrode was approximately 0.5 mm. The electric field of the laser beam was adjusted to be parallel (the π polarization) to the sheath electric field using a $\lambda/2$ plate. The laser beam transmitted through the plasma was detected using a photodiode.

A typical absorption spectrum is shown in Fig. 1, where a dc bias voltage of -160 V with respect to the ground potential was applied to the planar electrode. The origin of the horizontal axis corresponds to the center frequency of the $2p\,^2P^{\rm o}_{3/2} - 3d\,^2D_{3/2}$ transition line. The theoretical absorption spectrum was calculated by solving the time-independent Schrödinger equation with the perturbation of the electric field [2], and it was fitted with the experimental absorption spectrum. The parameters that were deduced by the fitting were the gas temperature and the electric field. The method of least squares was adopted to find the best fitting. The gas temperature and the electric field deduced by the fitting shown in Fig. 1 were 460 K and 650 V/cm, respectively. The electric field and the gas temperature, which were deduced by the spectral fitting, are summarized in Fig. 2 as a function of the electrode potential. The magnitudes of the error bars were evaluated on the basis of the ambiguity in the spectral fitting. We could not deduce the electric field at an electrode potential of 0 V, where the electrode potential was still lower than the plasma potential, since the ambiguity in the spectral fitting was too significant. As shown in the figure, we observed the monotonic increase in the electric field strength with the electrode potential. In contrast, we observed roughly constant gas temperature as a function of the electrode potential. This is a reasonable result since the heating of atomic hydrogen is not expected inside the nearly collisionless sheath at a pressure of 47 mTorr.

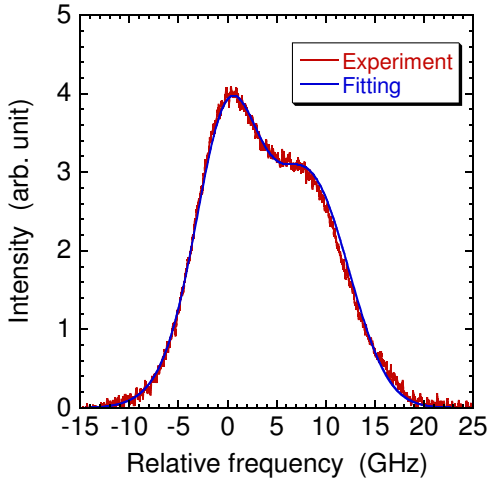

Fig. 1: Absorption spectrum of the hydrogen Balmer-α line observed at an electrode potential of -160 V.

The detection limit of the electric field was evaluated by comparing the theoretical field-free spectrum with the theoretical spectrum in an electric field. The difference between the two spectra was evaluated by the standard deviation. We have judged that the estimation of the electric field is possible if the difference between the field-free and in-field spectra exceeds the standard deviation between the theoretical and experimental spectra. As a result, it has been evaluated that the minimum electric field that can be determined by the present method is approximately 350 V/cm. This detection limit is comparable to the detection limits obtained by optogalvanic spectroscopy [3, 4] and laser-induced collisional fluorescence spectroscopy [5, 6], where pulsed dye lasers are used for exciting metastable states of helium and argon to Rydberg states with principal quantum numbers of $n = 7 - 14$.

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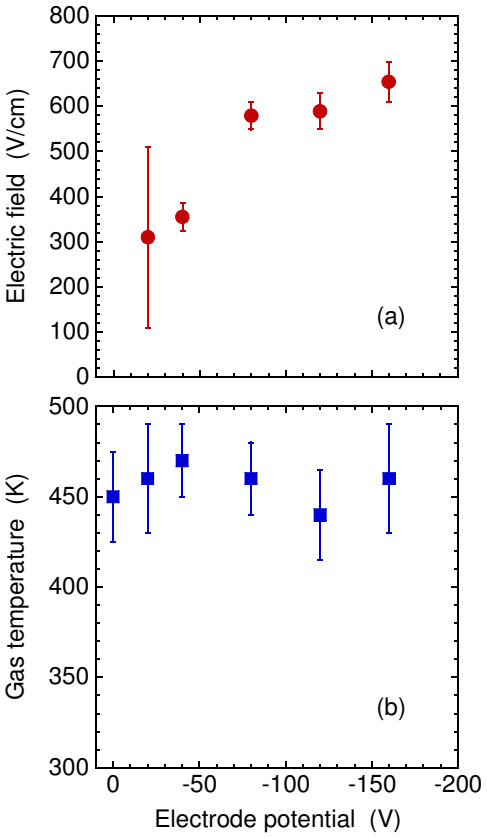

Fig. 2: (a) Electric field strength and (b) gas temperature, which are deduced by the fitting between experimental and theoretical spectra, as a function of the electrode potential.