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Spectroscopic study on the reflected neutral particles from solid surface

K. Kobayasi *, S. Ohtsu, S. Tanaka

Department of Quantum Engineering and Systems Science, School of Engineering, The University of Tokyo, 7-3-1 Hongo Bunkyo-ku, Tokyo, 113-0053 Japan

Abstract

Low energy hydrogen plasma was applied to copper, molybdenum and tungsten targets by the steady state linear plasma facility MAP (Material And Plasma) to study reflected neutral particles. The H_α (656.285 nm) spectra emitted from the reflected hydrogen atoms were measured to investigate the energy distribution and the angular distribution of the reflected hydrogen atoms. We found that the spectrum was composed of two groups. One is the low energy component (group 1) and the other is the high energy (group 2). The backscattered hydrogen atoms is found to be included in the group 2 spectrum from the results of the spectrum broadening and shift. The relation between the characteristics of target materials and reflection processes was also discussed.

Keywords: Hydrogen reflection; H_α emission; Spectroscopy; Copper; Molybdenum; Tungsten

1. Introduction

Particle reflection on the surface of the plasma facing material leads incident ions back into the plasma region as neutral atoms. The reflected neutral particles interact with plasma via excitation, ionization and charge exchange. These interactions cause radiation, energy loss and momentum transfer in the edge plasma region in the fusion devices. Thus the neutral particles have a strong effect on plasma transport. The neutral particles from the wall are considered to be generated by different types of processes; backscattering of incident ions and desorbing of neutrals in the material by diffusion and ion bombardment.

Hydrogen reflection has been studied experimentally but mostly at the energies above 1 keV. For the energy range of 1–100 eV, very few experimental data can be obtained. Aratari and Eckstein [1] have obtained the energy distribution of reflected hydrogen by ion beam bombardment and Cuthbertson et al. [2] have measured the energy distributions of the reflected oxygen and nitrogen by mass spectroscopy. Computer simulations about particle reflection have been done by the TRIM code [3,4], and a dynamical code [5].

In the present study, low energy hydrogen plasma was applied to the target materials in the linear plasma facility MAP [6,7]. We made spectroscopic measurements of the hydrogen spectrum to investigate the energy and angular distribution of backscattered neutral particles. The H_α (656.2849 nm) line of the Balmer series [8] was measured, since the intensity is strong enough for our high resolution spectroscopy. We used copper, molybdenum and tungsten as the target material. The energy of the backscattered particles was higher than that of the desorbed neutrals so that the emitted radiation of the backscattered neutrals appeared to have high spectrum broadening and spectrum shift near the target. The broadening, the wavelength shift and the intensity of the H_α spectrum depended on the target material. With this information, we can discuss the relation between the reflection process and the characteristics of the materials.

2. Experiment

The linear steady plasma facility MAP is schematically shown in Fig. 1. Low energy hydrogen plasma is

* Corresponding author. E-mail: kazuki@duke.q.t.u-tokyo.ac.jp.

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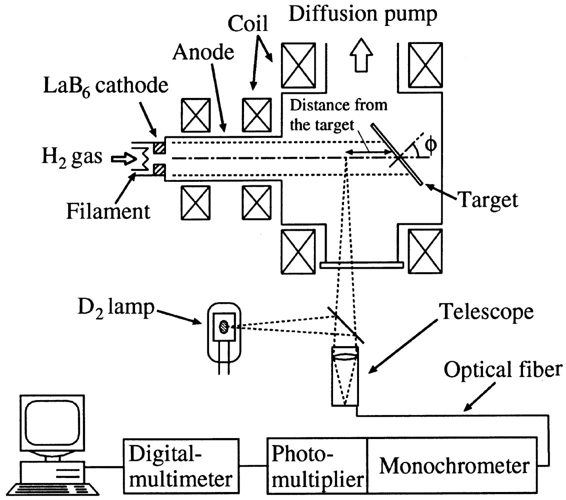

Fig. 1. Schematic diagram of the linear plasma facility MAP.

generated at the plasma source and applied to the target. The MAP consists of two parts, the plasma source chamber and the target chamber. In the plasma source chamber, hydrogen plasma is generated by the discharge between a LaB_6 cathode and a cylindrical pipe. The length and diameter of the plasma column is 70 and 3 cm, respectively. A neutral gas pressure of 5×10^{-2} Pa is achieved by a diffusion pump during operation. From Langmuir probe measurements [6,7], the plasma density is about $10^{13}/m^3$ and the electron temperature is about 10 eV in the hydrogen plasma. A magnetic field of about 350 Gauss is produced by four water-cooled coils. The target is installed to be inclined to the magnetic field so that we can make spectroscopic measurements at different incident angles to the target. The target plate is electrically insulated from the chamber to keep the target potential floating. According to the measurements of the electron temperature, the sheath potential is estimated to be about 30 eV, which corresponds to the energy of the incident ions.

The emission of the plasma is observed by a telescope with an optical lens of 4 cm diameter and 50 cm focal length. Therefore, we can observe the measurement area with 2 mm spatial resolution. This telescope is fixed on the X–Y stage and can be moved horizontally and vertically so that we can get the spatial profile of the H_α spectrum. A 1 m Czerny Turner monochromator with a photomultiplyer was used for the spectroscopy. The resolution of the monochromator in wavelength is 0.012 nm which is ascertained by measuring the referenced spectral line of a mercury lamp. To calibrate the wavelength of the obtained H_α spectrum, we used the D_α spectrum (656.103 nm) from a deuterium lamp. We placed a half mirror in front of the telescope and introduced the light of the deuterium lamp into the telescope. The direction of the telescope was perpendicular to the plasma column in all measurements.

We made the spectroscopic measurement all over the region of the plasma column, because the flux and the velocity distribution of the reflected hydrogen atoms vary with the distance from the target. The spatial change of the intensity, the wavelength shift and broadening of the H_α spectrum shows the energy and the angular distribution of the reflected hydrogen atoms. In the experiments of each target material, we set the target at the incident angle of $\phi = 0°$, 30°, 45° and 60° (Fig. 1) on the target surface to investigate the reflection angle of the hydrogen atoms.

3. Results and discussions

3.1. Decomposition of the H_α-spectrum

Fig. 2 shows the H_α spectrum obtained at 3 mm from the target surface in the experiment at 60° incident angle. The referenced D_α spectrum used to calibrate the wavelength is also shown in Fig. 2. We fitted a Gaussian curve to the D_α spectrum and determined the wavelength of the reference line (656.1032 nm) at the peak of the curve.

The H_α spectrum was found to be asymmetric near the target. The shape of the spectrum is slightly wider in the shorter wavelength side, which is the contribution of higher energy hydrogen atoms. To categorize the contribution of the hydrogen atoms to the H_α spectrum more clearly, we decomposed the H_α spectrum into two curves. We consider that the observed hydrogen atoms are composed of two energy groups. One is the hydrogen atoms dissociated from hydrogen molecules through the Franck–Condon process. The energy of these hydrogen atoms is a few eV. The other is the backscattered hydrogen atoms which have higher energy. Therefore, the spectrum is decomposed into two curves; the narrower curve (group 1) that represents low energy hydrogen atoms and the broader curve (group 2) that represents high energy hydrogen atoms. These curves are shown in

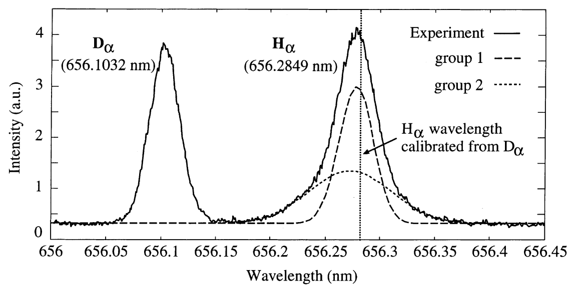

Fig. 2. Measured H_α spectrum and the decomposed curves. The D_α spectrum from the deuterium lamp is also shown.

Fig. 2 for group 1 by the broken line and for group 2 by the dotted line. H_α spectrum has the fine structure split ($3d^2D_{5/2,3/2}$–$2p^2P_{3/2}$ transition: 656.2849 nm, $3d^2D_{3/2}$–$2p^2P_{1/2}$ transition: 656.2732 nm) [9] and this split cannot be ignored. Both the group 1 and the group 2 curves consist of Gaussian curves of the same distribution that represent each splitted spectrum. In the evaluation of the spectrum broadening natural line width, Zeeman broadening and pressure broadening are negligible. Instrumental broadening is sufficiently small compared with the group 2 broadening and is ignored in the evaluation of the group 2 broadening.

3.2. Spectrum broadening

When the radiating atoms are in thermal equilibrium, the temperature of the radiating atoms T_{doppler} (eV) can be obtained from the Doppler broadening:

$$T_{\text{doppler}} = 1.69 \times 10^{8} \frac{\Delta\lambda^2 A}{\lambda_0^2}, \qquad (1)$$

where $\Delta\lambda$ is the full width at half maximum (FWHM) of the measured spectrum, A the mass number of the radiating atoms, λ_0 the wavelength of the spectral line. In our experiments, the plasma column is too small for backscattered hydrogen atoms to reach thermal equilibrium within the plasma. Therefore T_{doppler} does not mean the temperature of the backscattered hydrogen atoms. Nevertheless, we evaluated T_{doppler} to investigate the spatial change of the spectrum broadening in eV, because the T_{doppler} profile shows the spatial change of the average energy of the hydrogen atoms in the observing direction.

T_{doppler} of group 1 and group 2 in the copper and the tungsten target experiment are plotted as a function of the distance from the target in Fig. 3. The T_{doppler} profile of the molybdenum target experiment was the same as that of the tungsten target experiment. The center of the plasma column on the target surface is at 0 mm distance from the target. The measurements start from the edge of the target where the emission of the backscattered hydrogen atoms appears.

From Fig. 3, T_{doppler} of group 1 is about 0.5 eV which is constant in all measurements, while that of group 2 increases near the target. Hydrogen atoms are backscattered in large angular distribution. Thus the velocity distribution of the backscattered hydrogen atoms is broadened near the target. This leads the spectrum of backscattered hydrogen atoms to be broadened near the

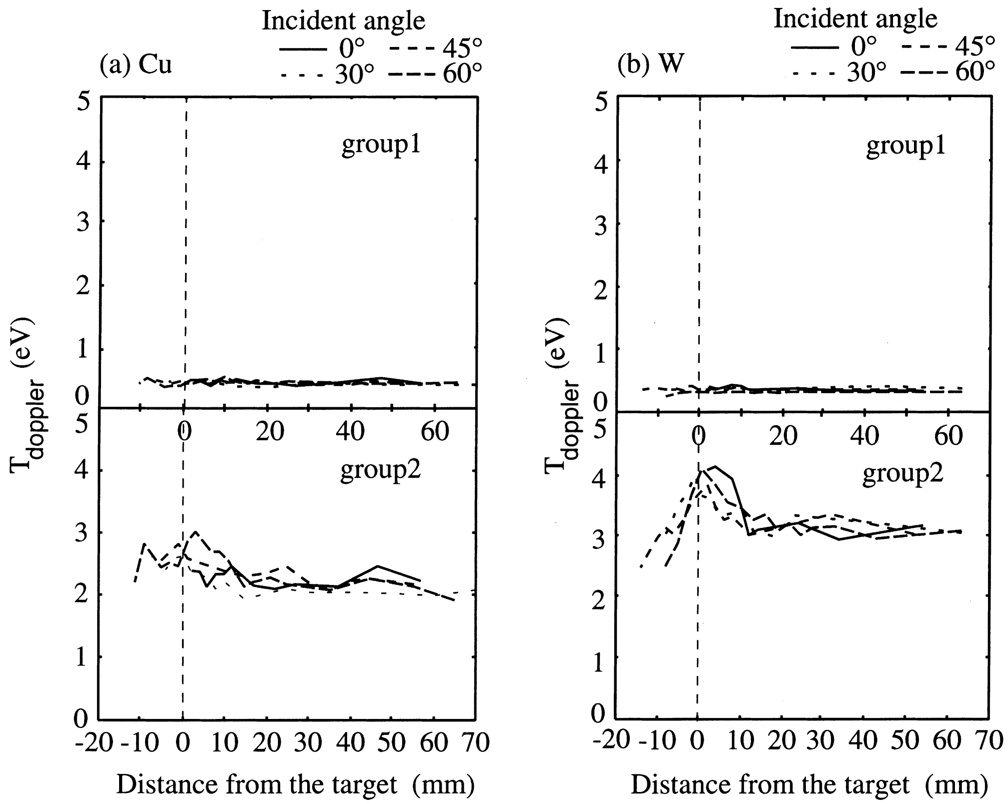

Fig. 3. T_{doppler} of the group 1 and the group 2 spectrum. (a) Copper target experiment; (b) tungsten target experiment.

target. Therefore, the group 2 spectrum is considered to have a contribution of high energy hydrogen atoms backscattered from the target.

In the molybdenum and the tungsten target experiment, T_{doppler} of group 2 increases to about 4 eV near the target, while it is less than 3 eV in the copper target experiment. This shows that the backscattering processes depend on the target material. Molybdenum and tungsten are body-centered cubic structures and copper is a face-centered cubic structure. The density of the number of atoms are $8.5 \times 10^{22}/\mathrm{m}^3$ in copper, $6.4 \times 10^{22}/\mathrm{m}^3$ in molybdenum and $6.25 \times 10^{22}/\mathrm{m}^3$ in tungsten. Copper is 1.3 times larger in the density of the number of atoms than molybdenum and tungsten. Therefore, we consider that the backscattering process depends on the crystal structure of the target material.

3.3. Spectrum shift

Fig. 4 shows the wavelength shift of group 1 and group 2 from 656.2849 nm which is the wavelength of the $3d^2D_{5/2,3/2}$–$2p^2P_{3/2}$ transition line. We can evaluate the collective motion of reflected hydrogen atoms along the observing direction. The velocity of this collective motion is

$$v = c\left(\frac{\lambda_0 - \lambda}{\lambda_0}\right) = c\left(\frac{\Delta\lambda}{\lambda_0}\right)(\mathrm{m/s}), \tag{2}$$

where c is the light speed, λ_0 the wavelength of the spectral line 656.2849 nm, λ the measured wavelength of the spectrum peak, and $\Delta\lambda$ the shift of the wavelength. $\Delta\lambda$ of group 2 increases with the increase of the incident angle near the target. This also indicates that group 2 represents the reflected hydrogen atoms. The maximum $\Delta\lambda$ of group 2 is less than 0.006 nm, which corresponds to the energy of 0.04 eV per atom. This value is too small compared to T_{doppler} of group 2 (3–4 eV). This indicates that the H_α lines of the backscattered hydrogen atoms are included in the shorter wavelength side of the group 2 curve. Thus the spectrum shift of the group 2 curve is smaller than that of the backscattered hydrogen atoms.

3.4. Intensity

Time dependence of the intensity of the H_α spectrum is shown in Fig. 5. We applied the plasma to the targets for more than 100 min and made spectroscopic measurements at intervals of several tens of minutes. The incident angle was fixed at 0°. In Fig. 5(a), the peak of intensity near the target arises in the copper target ex-

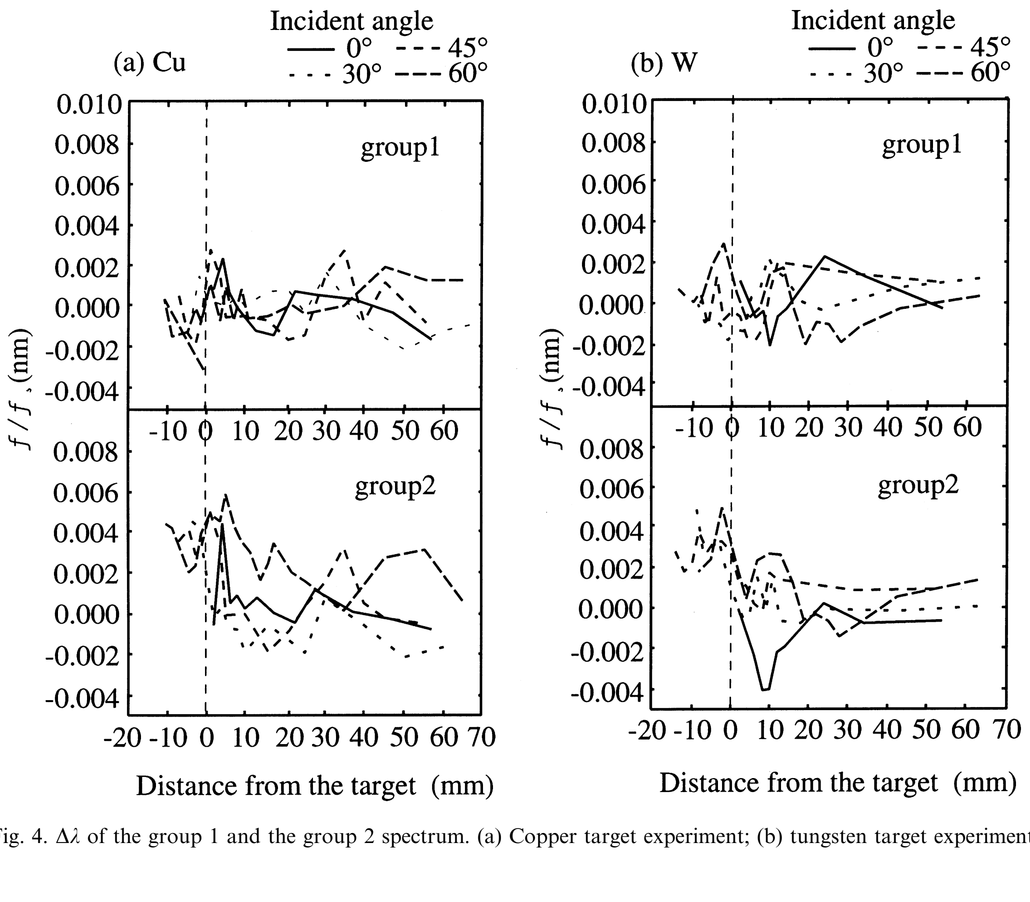

Fig. 4. $\Delta\lambda$ of the group 1 and the group 2 spectrum. (a) Copper target experiment; (b) tungsten target experiment.

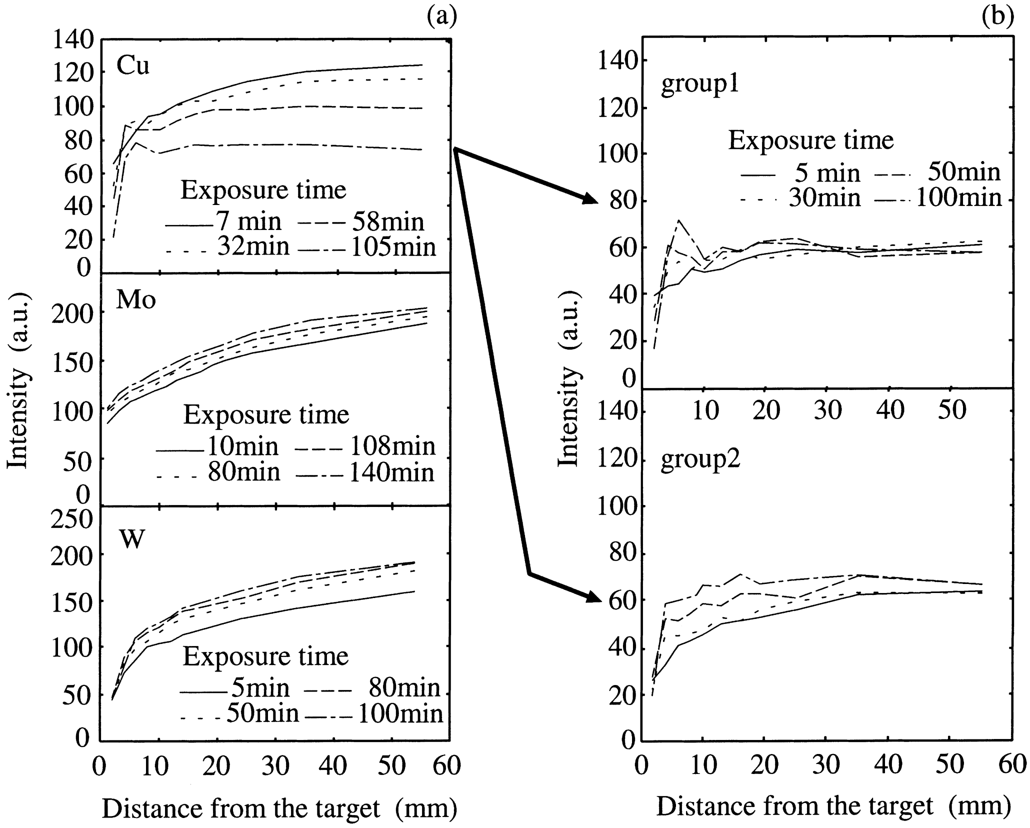

Fig. 5. Time dependence of the intensity of the H_α spectrum. (a) Intensity of the H_α spectrum in the copper, molybdenum, tungsten target experiments; (b) decomposed intensity of the group 1 and group 2 spectrum in the copper target experiment.

periments after a long discharge. Fig. 5(b) shows the decomposed intensity of the group 1 and group 2 curves in the experiment of the copper target. We can find that the intensity peak appeared due to group 1. The group 1 spectrum consists of low energy hydrogen atoms. This suggests that the thermal desorption process of the implanted hydrogen atoms changes according to the exposure time and depends on the target material. Surface analysis of the copper target by AES and RBS in each exposure time is required to specify the surface conditions.

4. Conclusions

Spectroscopic measurements of hydrogen spectra were performed on the linear plasma facility MAP to investigate the reflected hydrogen atoms from the solid surface.

We found that measured H_α spectrum can be decomposed into a low energy component (group 1) and a high energy component (group 2). From the dependence of the spectrum broadening and shift on the distance from the target and the incident angle on the target surface, it was found that the spectra of the backscattered hydrogen atoms are included in the group 2 curve.

It was discussed that the thermal desorption process related to the surface state changed after a long discharge from the results of the group 1 spectrum peak.

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