Measurements of Ion Temperature and Flow Velocity in Divertor Simulator MAP-II from Hydrogenic Helium Line Emission

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Ion temperature and flow velocity in the MAP-II divertor simulator plasmas were measured using a high-resolution spectrometer combined with image expander optics which can also correct the astigmatism in spherical mirrors. The fine structure of the hydrogenic helium line was taken into consideration in the fitting procedures. This enables the comparison of the absolute flow velocity measurements between spectroscopy and the Mach probe.

Keywords:

MAP-II, Flow, Ion temperature, He II, Fine structure, Divertor simulator

Plasma flow measurements are regarded as important in both core plasmas and divertor/edge plasmas. In the core regions, toroidal and poloidal plasma rotations, which relate to a radial electric field, play a role in plasma confinement properties. In the edge regions, plasma flows have significant effects on the particle recycling and transport phenomena, as well as being affected by the atomic and molecular processes, plasma-neutral frictions, and edge behaviors such as plasma detachment.

Charge-exchange spectroscopy (CXS) is a standard technique to obtain the local value of the plasma flow velocity in core regions. On the other hand, in divertor/edge plasmas or in divertor plasma simulators, a Mach probe, which is a sort of electrostatic probe having a directional dependence of the collection area, is widely used for the local measurements. In order to determine the flow velocity based on the Mach probe measurements, however, a proper model with a set of required parameters has to be applied depending on whether or not the probe is magnetized. Here, the word "magnetized" indicates the case in which the ion gyro-radius is smaller than the dimension of the probe head, while the other case is categorized as an "un-magnetized" Mach probe.

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The plasma conditions and the probe design in our experiments are the "unmagnetized" case [1] and the flow velocity can be expressed as

$$V_{\mathrm{f}} = \sqrt{\frac{kT_{\mathrm{e}}}{M_{\mathrm{i}}}} \sqrt{\frac{T_{\mathrm{e}}}{2T_{\mathrm{i}}}} \frac{j_{\mathrm{is}}^{+} - j_{\mathrm{is}}^{-}}{j_{\mathrm{is}}^{+} + j_{\mathrm{is}}^{-}}, \tag{1}$$

where, T_{e} and T_{i} are the electron and ion temperatures, respectively, M_{i} the ion mass, and j_{is}^{+} and j_{is}^{-} the ion saturation currents measured in upstream and downstream directions, respectively [2]. Namely, in order to evaluate the absolute value of V_{f}, the measurement of T_{i} is required.

From this point of view, spectroscopic measurements of the Doppler broadening and shift for ionic line emission in order to simultaneously obtain absolute values of T_{i} and V_{f} are quite useful for quantitative comparison with the Mach probe measurements, even though they provide line-of sight values. Usually, in low temperature (T_{e} < 10 eV) hydrogen-helium plasmas for divertor study, however, the comparison is not easy, not only due to the weak line strength of the helium ion emission but also due to the narrow Doppler broadening in which the fine structure splitting cannot be neglected.

In the present study, the ion temperature and the

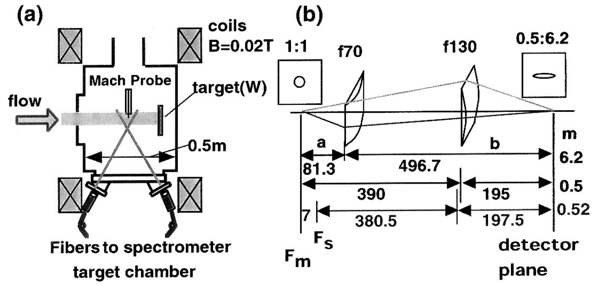

Fig. 1 (a) Target chamber in the MAP-II device and diagnostic arrangements. (b) Optical arrangement of an image expander. Astigmatism can be compensated for by the independent focus of the slit and spectral images. F_m and F_s are meridional(spectra) and sagittal(slit) focal points in the output of the 1-m spectrometer equipped with simple spherical mirrors, respectively.

ion flow velocity are measured in He plasmas using a He II (n = 3–4; 468.54 – 468.59 nm) emission which consists of 13 line components in the fine structure multiplet.

A schematic view of the experimental configurations in the target chamber of a steady-state divertor plasma simulator MAP (material and plasma)-II device [3] is shown in Fig. 1(a). The plasma diameter is about 50 mm. Viewing lines of the spectroscopy are located in +30 (blue shift) and –30 (red shift) degree directions with respect to the axis perpendicular to the flow direction, which enables the absolute calibration of the flow velocity [4].

A 1-m Czerny-Turner monochrometor with a 2,400 grooves/mm grating is used. The instrumental width (FWHM) for a slit width of 0.020 mm is 0.017 nm, which corresponds to only 2 or 3 pixels in typical commercial-base charge-coupled device (CCD) detectors having a pixel size of 0.02–0.03 mm. Since the FWHM of the Doppler broadening for 1 eV helium ion temperature in this wavelength is 0.018 nm, and since the fine structure splitting is much broader, the spectral profile needs to be expanded in order to resolve the subtle difference of the broadenings and of the Doppler shifts in each sight line.

For this purpose we have designed image expander optics which are inserted between the spectrometer and CCD. As shown in Fig. 1(b), a pair of cylindrical lenses is used. One has a focal length f of 70 mm with respect to the meridional (dispersion) axis while the other has that of 130 mm with respect to the sagittal (slit) axis. The output image of the spectrometer is then cast onto the detector plane at a distance of 585 mm with magnifications of 6.2 and 0.5 in the meridional and sagittal directions, respectively.

Even if the spectrometer is not equipped with toroidal mirrors for the astigmatism correction, the sagittal image can be corrected by only the small displacement of a f = 130 mm lens. The deviation between the sagittal and meridional focal points at the exit port in our spectrometer is 7 mm due to the astigmatism in the spherical mirrors. With the object and image distances a and b from the lens of focal length f, a corrected thin lens equations, $1/a + 1/b = 1/f$, for meridional and sagittal optics can be determined as (a, b, f, a+b, m)=(81.3, 496.7, 70, 585.0, 6.2) and (380.5, 197.5, 130, 578.0, 0.52) [mm], respectively, where, $m(=a/b)$ is the transverse magnification. Fine adjustment of the lens positions are then made to yield best focus in the both meridional and sagittal images.

Therefore, detailed line profiles having fine structure components became available for each spatial channel. Note that the use of a photo-multiplier tube in rotating the grating angle for increasing the data points cannot avoid the mechanical jitter in the scanning instrumentations which causes a wavelength uncertainty of about 0.01nm, thus making it non-applicable for this purpose.

Fig. 2 shows the line profiles of the hydrogenic helium line He II around 468.57 nm, obtained in the He discharges in MAP-II together with the relative strength of the fine structure multiplet and with the fitting curve

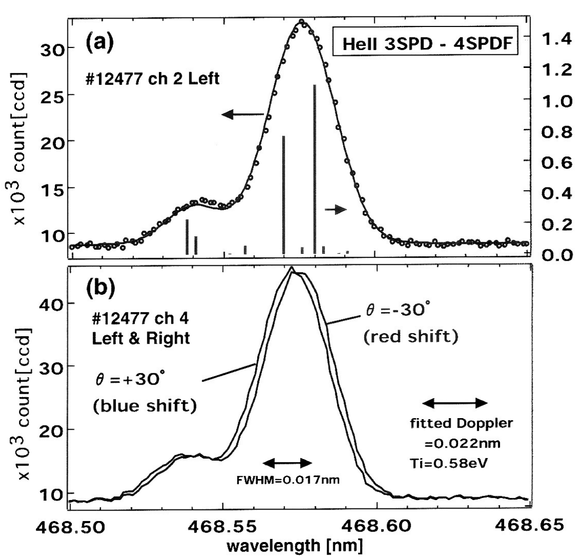

Fig. 2 (a) Multi-gaussian fitting curve (line) to the measured line profile (dot). (b) Measured red and blue Doppler-shifted spectral profiles.

in the form of the following function with respect to the wavelength λ,

$$I(\lambda) = I_0 \sum_{l=1}^{13} (2J_l + 1) A_l \exp\left\{ -\left(\frac{\lambda - \lambda_0 - \lambda_l}{\lambda_{1/e}} \right)^2 \right\}. \quad (2)$$

The fitting parameters are the amplitude I_0, gaussian line broadening $\lambda_{1/e}$, and the whole Doppler shift λ_0. The given parameters are the wavelength, total angular momentum quantum number, and the Einstein coefficients for lth components λ_l , J_l , and A_l, respectively, where line label l = 1 – 13.

Use of the Einstein's spontaneous emission coefficients for the hydrogen Paschen-alpha emission multiplied by the statistical weight $(2J_l+1)$ of the upper level can accurately reproduce the measured line profile, as seen in the figure.

The ion temperature and the flow velocity can be determined based on the fitting results. As shown in Fig. 2(b), red-shifted and blue-shifted profiles can clearly be resolved. The measured values of T_i and V_f in the central chord are 0.58 eV and 1.23 km/s, respectively. Although the error bar in T_i estimated from the fitting errors of the base line, width, and amplitude is about 40 – 50 %, the reproducibility of the values is much higher. On the other hand, the fitting error bar for the flow velocity is much smaller than one percent.

The flow velocity measured using the Mach probe from eq.(1) with T_i and T_e obtained from He II line spectra and current-voltage characteristics of the Mach probe, respectively, is about 2 km/s in the plasma center and decreases with the plasma radius. Therefore, we have shown that this technique provides T_i and V_f values with a high degree of accuracy. The reliability of the local flow velocity with the Mach probe can then be much more improved by using T_i and by comparing V_f between both measurements [5]. This will be further investigated in the future.

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