Spectroscopic Measurements of Ion Temperature in Sheet Plasma and String Plasma

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(Received June 17, 1996)

KEYWORDS: spectroscopic measurement, ion temperature, sheet plasma, string plasma, magnetic field, Larmor radius, emission spectra

An emission spectrum shows a broadening or a shift of line due to thermal or collective motion of the emitted species. From such broadening or the shift, it is possible to determine the temperature of ion and atom. Key parameters of a plasma are the temperature and the densities of both ion and electron. Among these parameters, the temperature and the density of electron are determined by a Langmuir probe, while the density of ion is assumed to be identical with that of electron. The temperature of ion has been obtained from the method of an energy analysis such as a Faraday cup or from an emission spectroscopy mentioned above. The uncertainties, however, remain at the Faraday cup when the plasma is confined magnetically.

It is, thus, the purpose of this paper to measure spectroscopically the temperature of ion in both a sheet plasma and a string plasma whose thickness or diameter is approximately equal to twice the mean ion Larmor radius, which are produced by originally designed TU-2 and ST-1 devices1,2, respectively, and to show how the operational parameters, such as a discharge voltage, a gas flow rate and a magnetic field, affect the ion temperature. Since a Larmor radius of ion is related to the ion temperature and to the strength of the magnetic field, it is also another attempt of this paper to demonstrate the extent to which the calculated Larmor radius meets the previously reported Larmor radius $r_p$ which was determined from the measured density profile with the Langmuir probe3. Although the emitted spectrum was measured firstly from the direction perpendicular to the flow of string plasma in a preliminary experiment, some extent of the self absorption was observed at the peak of the emitted line due to a long path of emitted spectrum through the flow of plasma. Efficient analysis was, thus, possible only when the emitted spectra were taken from the direction parallel with the flow of plasma through the side window as shown in Fig. 1.

Applying the Maxwell distribution law to the species in present plasma, we can obtain the ion temperature $T_i$ from the usual equation as3:

$$T_i = 1.7 \times 10^8 \left[ \frac{\Delta \lambda D_1/2}{\lambda_0} \right]^2 A,$$

where $T_i$ is expressed in eV, the half width of the peak $\Delta \lambda D_1/2$ and the wave length at the peak $\lambda_0$ are expressed in nm, and $A$ is the mass number of ion. The emission spectrum was passed through the lens 1 (105 mm in diameter, 359.5 mm in focal distance) reflected by three mirrors and passed again through an achromatic lens 2 (65 mm in diameter, 500 mm in focal distance) as shown in Fig. 1. The emission spectra were analyzed by a Spex 1404 double spectrometer to provide the variation of line intensity with the wave length. The obtained spectrum could be transduced into electric voltage by a photomultiplier (Hamamatsu Photonics R928). The output of the photomultiplier was printed with a X-t recorder followed by the reading of the half width of the peak or stored in a computer followed by the computational procedure for determining $T_i$. Since the spectrum of argon in the sheet plasma or in the string plasma shows a strong peak at ArII-434.806 (4P-4D0) nm, such a peak is used for getting the half width in order to calculate the value of $T_i$. In addition to $T_i$, the temperature of electron $T_e$ and the density of plasma $n_p$ which is equal to the density of electron $n_e$ are measured simultaneously with the Langmuir probe. The resolution depends mainly on a slit width, being 0.372 nm at the slit width of 12 $\mu$m for the emission spectrum. Since a Larmor radius of ion is related to the ion temperature and to the strength of the magnetic field, it is also another attempt of this paper to demonstrate the extent to which the calculated Larmor radius meets the previously reported Larmor radius $r_p$ which was determined from the measured density profile with the Langmuir probe3. Although the emitted spectrum was measured firstly from the direction perpendicular to the flow of string plasma in a preliminary experiment, some extent of the self absorption was observed at the peak of the emitted line due to a long path of emitted spectrum through the flow of plasma. Efficient analysis was, thus, possible only when the emitted spectra were taken from the direction parallel with the flow of plasma through the side window as shown in Fig. 1.

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Fig. 1 Schematic drawing of an optical system
the 1404 spectrometer.

1. $T_i$ in Sheet Plasma and the Larmor Radius of Ion in Sheet Plasma

The variations of $T_i$ with the gas flow rate $Q_{Ar}$ have been plotted in Fig. 2(a) for setting the discharge current $I_d$ and the magnetic field $B$ equal to be constant. The values of $I_d$ are selected as 12, 15 and 20 A and those of $B$ are 0.185 and 0.247 T, while the pressure $P_e$ in the experimental region is kept at $1.3 \times 10^{-3}$ Pa. A glance at this figure shows that $T_i$ is inversely proportional to $Q_{Ar}$. It seems that the decrease in $T_i$ with increasing gas flow rate is mainly due to the high frequency of collision between ion or electron and the increased neutral particle in the discharge region.

The calculated Larmor radius $r_s$ from the obtained $T_i$ is indicated in Fig. 2(b). The minimum value of $r_s=6.5$ mm under the experimental condition such as $Q_{Ar}=20$ sccm, $I_d=12$ A and $B=0.247$ T is larger than the value of $r_p=2$ mm which is assessed from the measured half width of the density profile in the direction of the thickness of sheet plasma by using the Langmuir probe. Such a small value obtained from the previous experiment(4) is considered that centrally localized electrons in the sheet plasma interact strongly with the peripherally-rotating ions due to the Larmor motion.

2. $T_i$ in String Plasma and the Larmor Radius of Ion in String Plasma

The curves in Fig. 3(a) show the values of $T_i$ as a function of $B$ at various $I_d$ and $Q_{Ar}$. The selected values of $I_d$ are 4, 8 and 12 A and those of $Q_{Ar}$ are 0.3 and 0.6 sccm. The value of $T_i$ increase proportionally with increasing $B$ as shown in Fig. 3(a). It was found from the preliminary experiment that while the pressure $P_d$ in the discharge region increases from 100 to 200 Pa with increasing $B$, the $T_i$ also increases as $P_d$ increases. Since the neutral particle increases as the pressure increases, it is known extensively that the temperature of ion electron decreases with increasing pressure due to the increased collision between ion or electron and neutral particle. By contrast with such a simple explanation mentioned above, the following interpretation of unexpected increase in $T_i$ may be given; the flow of ion through small hole in the anode, i.e., 1 mm in diameter, along with the pressure difference produces the greatly increased population of ion at some point of the hole due to the strong repulsion between ion and anode, the motion of such increased population of ion toward the cath-

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**Fig. 2** Variation of both $T_i$ and $r_s$ with $Q_{Ar}$, at various $B$ and $I_d$ for the sheet plasma (TU-1)

The pressure $P_e$ is $1.3 \times 10^{-3}$ Pa in the experimental region. $T_i$ was determined from the linewidth of ArII-434.86 nm line.

**Fig. 3** Variation of both $T_i$ and $r_s$ with $B$ at various $I_d$ and $Q_{Ar}$ for the string plasma (ST-1)

The pressure $P_e$ is $1.3 \times 10^{-3}$ Pa in the experimental region.
ode, therefore, restricts significantly the flow of electron and neutral particle, giving rise to the increase in the pressure at discharge region. In other words, the long retention time of ion at discharge region allows to increase $T_i$ due to the increased collision between ion and electron.

The calculated Larmor radius from obtained $T_i$ is shown in Fig. 3(b). The minimum value $r_s=5\,\text{mm}$ is obtained when $Q_{Ar}=0.6\,\text{sccm}$, $I_d=8\,\text{A}$ and $B=0.3\,\text{T}$. This minimum value is still large, in comparison with the value of $r_p=1\,\text{mm}$ obtained from the measured half width of the density profile in the radial direction of string plasma. It is also clear from the above fact that the centrally localized electrons in the string plasma interact with the peripherally-rotating ions. Although the treatment based on the Maxwell distribution law fails to take account of interaction between the centrally localized electrons and the peripherally-rotating ions, it may provide a basis for consideration of the effect of electric field on the velocity distribution of species in plasma.

The authors wish to express their gratitude for the financial assistance from Grant-in-Aid for General Scientific Research (C), No.08680513, the Ministry of Education, Science, Sports and Culture.

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