Determination of Parallel and Perpendicular Ion Temperatures Based on Selective Ion Transmission in a Retarding Field Analyzer

Shigetaka KAGAYA, Hiroyuki TAKAHASHI, Tomohiro SEINO, Keigo YOSHIMURA, Ryota NISHIMURA, Akihiro KANNO, Yusaku TAKAHASHI, Tomoya HARA, Tetsutarou OISHI, Akinobu MATSUYAMA[1)] and Kenji TOBITA

Department of Quantum Science and Energy Engineering, Tohoku University, Sendai 980-8579, Japan
[1)]*Graduate School of Energy Science, Kyoto University, Uji 606-8501, Japan*

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This work reports a novel approach employing a retarding field analyzer (RFA) to simultaneously measure parallel and perpendicular ion temperatures. *I-V* curves obtained by the RFA were analyzed considering the influence of selective ion transmission, and the ion temperatures were evaluated. The RFA analysis yielded parallel and perpendicular ion temperatures of 1.2 eV and 2.1 eV, respectively. The perpendicular ion temperature obtained by an ion sensitive probe was 2.0 eV, demonstrating good agreement with that evaluated by the RFA.

Keywords: retarding field analyzer, selective ion transmission, ion temperature, radio-frequency plasma, DT-ALPHA

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In open magnetic systems, such as SOL-divertor plasmas, convective losses of parallel components of ion energy typically exceed those of the perpendicular components unless collisional relaxation progresses sufficiently. This potentially leads to anisotropy in ion temperatures. Kinetic and fluid simulations for SOL-divertor plasmas have demonstrated the emergence of significant temperature anisotropy [1–3]. This anisotropy is believed to influence heat loads and the physical sputtering of plasma-facing components. However, experimental investigations focusing on such temperature anisotropy are limited due to challenges associated with simultaneous measurements of parallel and perpendicular ion temperatures ($T_i^{\parallel}$ and $T_i^{\perp}$). This study aims to develop a novel technique allowing simultaneous measurements of the two ion temperature components using a retarding field analyzer (RFA).

RFAs were originally developed to measure $T_i^{\parallel}$ and have been utilized in tokamaks and stellarators [4–6]. RFAs typically feature narrow entrance slits at the plasma-facing sections. However, for use in small linear devices, a different type of RFAs equipped with a circular aperture has been proposed.[7, 8]. Recently, the influence of ion Larmor motion on use of these aperture-type RFAs has been investigated based on simple numerical calculations [9]. The results indicate that the ion Larmor motion results in selective ion transmission, deforming the *I-V* curves. Furthermore, Ref. [9] has proposed the concept of evaluating $T_i^{\parallel}$ and $T_i^{\perp}$ from a single *I-V* curve utilizing selective ion transmission. This concept potentially enables observations of anisotropic ion temperatures with an RFA. However,owing to the lack of experimental investigations, the feasibility of the concept remains unclear. This paper presents the results of the first experimental implementation of this concept, as well as a comparison between $T_i^{\perp}$ obtained by an RFA and an ion sensitive probe (ISP).

In this study, experiments were conducted within the radio-frequency (RF) plasma device DT-ALPHA [10]. Helium plasma was produced by 13.56 MHz RF discharge. The cross-section of the RFA mounted within the DT-ALPHA device is illustrated in Fig. 1 (a). The RFA comprises an aperture (6 mm in diameter), three grids, and a collector. Figure 1 (b) depict the potential structure within the RFA. In addition to the RFA, an ISP was also mounted within the DT-ALPHA device. Details regarding the ISP can be found in Ref. [11]. The RFA and ISP measurements were conducted in the central region of the cylindrical plasma. To mitigate the space-charge limitations, low-density plasma was employed in this experiment. The magnetic field strength in this region was 0.13 T. A Lang-

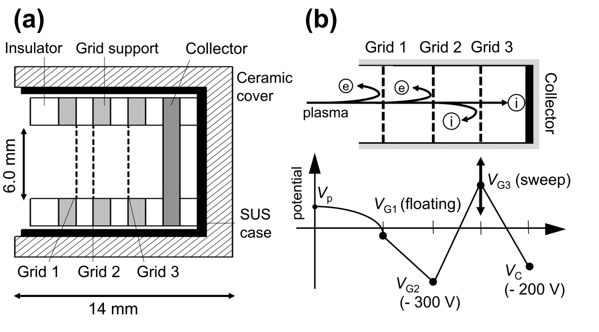

Fig. 1 (a) Cross-section of the RFA, and (b) potential structure within the RFA.

author's e-mail: shigetaka.kagaya.q7@dc.tohoku.ac.jp

muir probe mounted near the plasma production region yielded an electron temperature of approximately 14 eV and a density of 4.5×10^{15} m^{-3}.

When considering ion Larmor motion, the collector current of an RFA (I_C) can be described as follows [9]:

$$I_C = 2\pi q n_i \int r\mathrm{d}r \int_0^{\infty} \int_{v_\parallel^{\min}}^{\infty} f(v_\parallel, v_\perp) v_\parallel v_\perp \mathrm{d}v_\parallel \mathrm{d}v_\perp, \quad (1)$$

where n_i and q denote the ion density and the ion charge, respectively. $f(v_\parallel, v_\perp)$ represents the Maxwellian distribution function of parallel and perpendicular velocities $(v_\parallel, v_\perp)$. $v_\parallel^{\min}$ represents the minimum parallel velocity of detectable ions. In conventional RFA analyses, $v_\parallel^{\min}$ is determined by the ion retarding potential. However, when considering the ion Larmor motion, $v_\parallel^{\min}$ also depends on the ion Larmor radius and the position of the ion guide center (r). This effect limits the ranges of parallel and perpendicular velocities of detectable ions, resulting in the deformation of *I-V* curves corresponding to $T_i^\perp$. Using this characteristic, $T_i^\perp$ can be determined by identifying the $T_i^\perp$ value that best reproduces the experimentally obtained *I-V* curve.

Figure 2 (a) presents a typical *I-V* curve obtained by the RFA. V_{ret} represents the effective ion retarding potential (grid three potential minus plasma potential). The collector current exhibits an exponential decrease above the plasma potential, where $V_{ret} = 0$ V. $T_i^\parallel$ evaluated from the slope of the curve was approximately 1.2 eV. Notably, the ion saturation current was significantly smaller than the space-charge-limited current derived using the formula proposed in Ref. [12], indicating that the measurement was not affected by space-charge limitations. Using this $T_i^\parallel$ and various $T_i^\perp$ values, *I-V* curves were calculated and compared with the experimentally obtained curve. Figure 2 (b) summarizes the results. Here, the vertical axis represents the normalized collector current at the plasma potential. As depicted in Fig. 2 (b), the calculation with $T_i^\perp = 2.0$ eV reproduces the experiment better than those with 1.0 eV and 3.0 eV. The most reasonable $T_i^\perp$ was evaluated using an evaluation function defined as follows:

$$f_{er} = \sum_{V_{G3}} \left(\frac{I_{exp} - I_{calc}}{I_{exp}} \right)^2, \quad (2)$$

where I_{exp} and I_{calc} represent the experimentally obtained and calculated collector currents. Figure 2 (c) depicts the evaluation function f_{er} as a function of $T_i^\perp$. As depicted in Fig. 2 (c), f_{er} was minimized at $T_i^\perp = 2.1$ eV, indicating that the calculation with $T_i^\perp = 2.1$ eV yields the best reproduction. To validate this $T_i^\perp$, ISP measurements were conducted. Figure 2 (d) presents an *I-V* curve obtained with the ISP. The exponential decay part of this curve indicates that $T_i^\perp = 2.0$ eV, exhibiting good agreement with the value obtained by the RFA analysis.

In summary, parallel and perpendicular ion temperatures were evaluated using an RFA, and results were compared with those obtained using an ISP. Analysis of the RFA considering the influence of selective ion transmission yielded value of $T_i^\parallel = 1.2$ eV and $T_i^\perp = 2.1$ eV. The perpendicular ion temperature obtained with the ISP was 2.0 eV, exhibiting good agreement with that evaluated by the RFA. These results substantiate the potential utility of this technique for investigating ion temperature anisotropy predicted by numerical calculations and its impact on divertor heat load and sputtering.

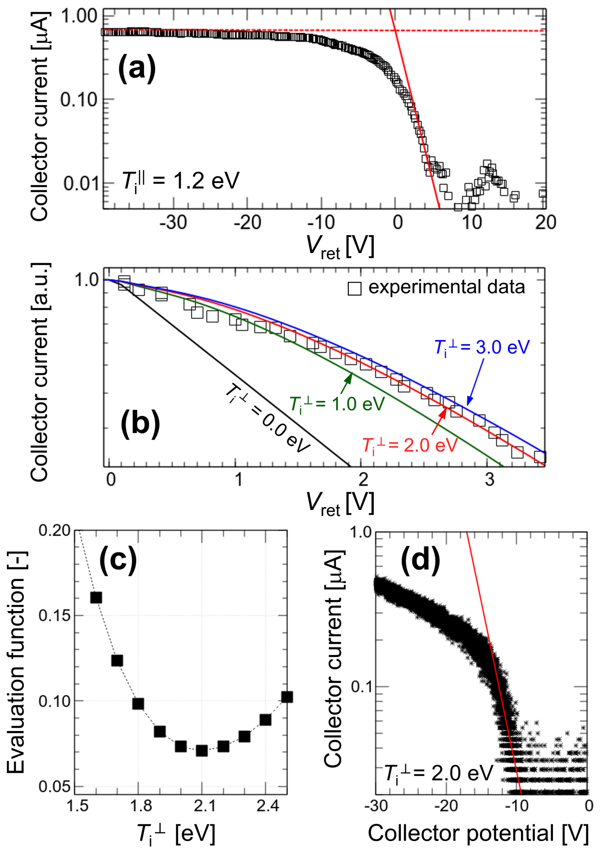

Fig. 2 (a) *I-V* curve obtained with the RFA, (b) comparison with calculations, (c) f_{er} defined in Eq. (2) as a function of $T_i^\perp$, and (d) *I-V* curve obtained with the ISP.

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