Observation of the Plasma Flow Effect on Ion Temperature Measurements using a Retarding Field Analyzer

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A retarding field analyzer (RFA) was designed for the ECR plasma device HYPER-I, making ion temperature (T_i) measurements possible for the first time. Using argon plasma, T_i was measured by rotating the RFA relative to the magnetic field lines in 90-degree increments, while maintaining a constant radial position and discharge conditions. Consistently higher T_i was observed when the RFA was exposed to axial and rotational plasma flows, whereas lower values were measured when it was oriented in the downstream directions. Such discrepancies in T_i are expected to remain robust across devices when RFAs are used in plasmas with significant flow.

Keywords: retarding field analyzer, ion temperature, plasma flow, argon, HYPER-I, ECR

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One of the most practical methods for performing *in situ* measurements of ion temperature (T_i) is the retarding field analyzer (RFA). RFAs have been used extensively in various plasmas, including space plasma [1, 2], laboratory plasma [3, 4], and magnetically confined plasma [5]. Recent work on a radio-frequency plasma reported that different T_i values were obtained depending on whether an RFA faced the upstream or downstream direction of the plasma flow [6]. Comparisons across devices are expected to show that this trend is commonly observed in T_i measurements based on RFAs. In this study, we developed a compact RFA and measured T_i in the ECR plasma device HYPER-I.

Figure 1(a) shows a top view of the HYPER-I [7]. The HYPER-I, which consists of a cylindrical vacuum chamber (SUS) and 10 magnetic field coils, is a linear plasma device designed for a variety of basic plasma experiments. The inner diameter of the chamber is 0.3 m, and its axial length is 2.0 m. Plasmas are generated by ECR heating using a 2.45 GHz microwave supplied through a tapered waveguide connected to the vacuum chamber at $z = 0$. The RFA was mounted on the lower port at $z = 1.4$ m, where the magnetic field strength was $B = 65.2$ mT, respectively. In this experiment, argon plasma was generated, and the neutral pressure and discharge power were maintained at approximately 0.011 Pa and 6 kW, respectively. Figure 1(b) shows an enlarged image of the developed RFA. The size of the RFA is the same as that of the one operated in the DT-ALPHA device [6], and it was fabricated in a similar manner. Four electrostatic grids and one ion collector are mounted inside the cylindrical RFA volume. Each grid is made of SUS and has a mesh size of 200 mesh/inch. The potentials of the grids and the collector can be controlled independently. Starting from the plasma-facing side, each grid is referred to as grid #1 through grid #4, respectively. During the experiments, the potentials of grids #1 and #2, and of the collector, were maintained at the floating potential, −170 and −70 V, respectively. The potential of grid #3 was swept from −100 to 100 V, to obtain the *I*–*V* curves. The grid #4 was negatively biased (−100 to −600 V) to return secondary electrons emitted from the collector surface. *I*–*V* curves were obtained by changing its orientation relative to the magnetic field lines in 90-degree increments, as shown in Fig. 1(c). When the RFA is oriented in the “upstream” direction, the RFA faces the axial plasma flow. Rotating it by 180 degrees causes it to face the “downstream” direction of the flow. Although this is not indicated in Fig. 1(c), the plasma also exhibits azimuthal rotation, driven primarily by the $\mathbf{E} \times \mathbf{B}$ force, with the flow direction varying according to the discharge conditions. The RFA was located in the lower half of the plasma column, several centimeters from the center.

Figure 2 shows typical *I*–*V* curves obtained when the RFA was oriented toward the upstream and downstream sides. The potential of grid #4 was −200 V. Horizontal axis represents the potential of grid #3. Panels (a) and (b) show the full curves, and panels (c) and (d) show enlarged views on a semi-logarithmic scale. As shown in Figs. 2(a) and (b), the collector current reached saturation when the potential of grid #3 was highly negative. It approached nearly zero when grid #3 was swept to a strongly positive potential. In Figs. 2(c) and (d), a clear exponential decay was observed. The slope indicated T_i values of approximately 2.1 and 1.5 eV for measurements toward the upstream and downstream sides, respectively.

As varying the RFA orientation, T_i was measured and

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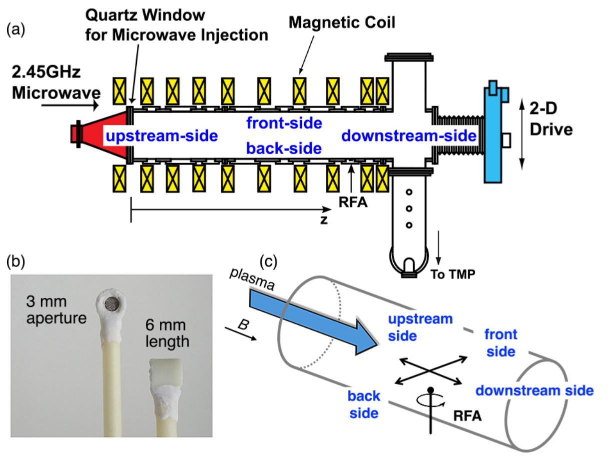

Fig. 1. (a) Top view of HYPER-I, (b) enlarged view of the RFA head, and (c) the orientation of the RFA. The RFA was installed on the lower port at z = 1.4 m.

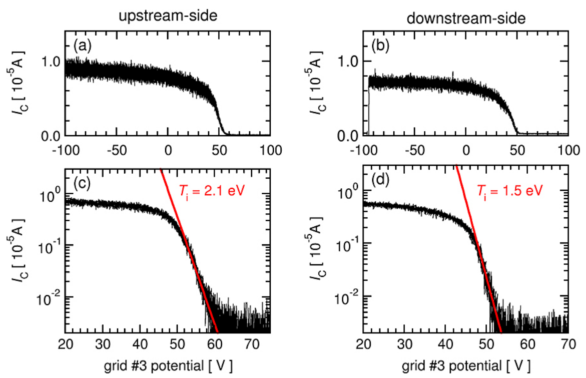

Fig. 2. Typical I–V curves obtained when the RFA was oriented toward the upstream and downstream sides of the device. (a) and (b) show the full curves. Enlarged views are shown in (c) and (d). The potential of grid #4 was −200 V.

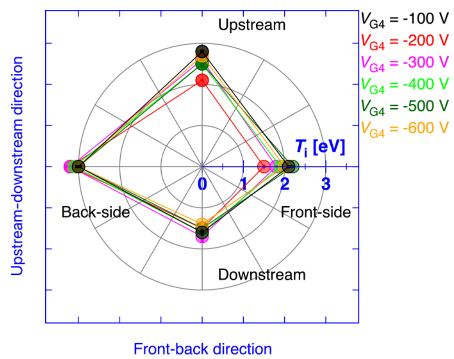

Fig. 3. Polar chart of ion temperature obtained for different RFA orientations. Different legends correspond to different grid #4 potentials.

the results were summarized in Fig. 3. The value of T_i is represented by the radius of the polar chart. Regardless of the grid #4 potential, the RFA consistently measured a higher T_i (2–3 eV) when exposed to axial and azimuthal plasma flows, whereas lower values (1–2 eV) were obtained when it was oriented downstream of the flows. Ratios of T_i between upstream and downstream measurements, as well as between back-side and front-side measurements, were approximately 1.5–2. The axial plasma flow velocity and T_i measured using the laser-induced fluorescence (LIF) method under the same discharge conditions as in this study are approximately 0.9 km/s and 0.7 eV, respectively. The T_i ratio calculated from these values using the model proposed in Ref. 6 ranges from 1.4 to 1.5, indicating that the effect of axial plasma flow can explain the observed T_i ratio. Here, the T_i values obtained using the RFA and the LIF method differ by approximately 1 eV. Because the laser path was aligned to measure the plasma center whereas the RFA head was mounted several centimeters away from the center, the difference in their measurement locations is considered one possible reason for the discrepancy in T_i. Plasmas generated in the HYPER-I device can develop an azimuthal flow in the counterclockwise direction [8]. Assuming a radial electric field of approximately 0.1 V/mm at the RFA head position, the $\mathbf{E} \times \mathbf{B}$ flow speed is estimated to be approximately 1.5 km/s under the magnetic field strength used in this experiment. Because this estimated azimuthal flow speed is comparable to the axial flow speed measured by the LIF method, the differences in the T_i values obtained between the front and back sides may also be attributed to the azimuthal flow effect.

In summary, the effect of plasma flow on T_i measurement based on the RFA was observed in HYPER-I. Regardless of the direction of the plasma flow, systematically higher T_i was obtained when the RFA was exposed to the incoming plasma flows. In contrast, the RFA yielded lower T_i when it was oriented in the downstream direction of the plasma flow. Similar discrepancies have also been observed in another plasma device [6], suggesting that this trend is widespread in the use of RFAs under conditions of significant plasma flow. Performing similar experiments while varying the RFA position will further improve understanding of the plasma flow effect. In addition, the measurement of T_i using the LIF method is planned to compare T_i obtained by the RFA.

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