Selective Heating of Helium Ion in Magnetized Sheet Plasma

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Ion cyclotron resonance heating in the magnetized sheet plasma is studied experimentally in a linear plasma device, TPD-SheetIV. We have demonstrated the ICRH of the helium or helium/hydrogen mixture sheet plasma by the RF electrodes of two parallel plates, sandwiching the sheet plasma. Measurements of the ion temperature in the plasma were carried out by a Faraday cup. In addition, the ion densities in the plasma were measured by an omegatron mass analyzer. The resonance frequencies f_{RF} is slightly higher than the ion cyclotron frequency of helium f_{ci}. The ion densities N_i of He^+ rapidly decreases with increasing the P_{RF}, although H^+ and H_2^+ gradually decrease.

Keywords: Ion cyclotron resonance, sheet plasma, omegatron mass analyzer, Faraday cup

1. Introduction

Ion cyclotron resonance heating (ICRH) of plasma can be applied to mass separation with a small fractional mass difference. This technique of the separation can be applied to many applications, such as, separation of deuterium and helium-3 for the fuels of nuclear fusion, selective removal of helium from nuclear fusion reactor [1], and recycling of optical-fiber, and so on.

The first successful experiment to demonstrate this idea was carried out by Takayama and his coworkers at the Institute of Plasma Physics, Nagoya [2]. They observed the effect of mass separation in helium plasmas with impurities in a line cusp. Dawson et al. [3] observed the enrichment of ^{41}K in potassium samples collected on cooled tungsten ribbons after selective heating of ^{41}K ions by ICRH in cylindrical plasma with a large cross-sectional area. However, when the plasma density is raised so as to increase the collected amount of desired isotopic species, the effect of collisions among charged particles tends to suppress heating of ions of the desired species, resulting in significant degradation of the separation efficiency.

In order to overcome this problem, Takayama has proposed to perform mass or isotope separation by ICRH in a sheet plasma which is a special type of strongly magnetized highly ionized slab plasma [4,5]. The sheet plasma has thickness which is as thin as twice the mean ion Larmor radius, in a direction perpendicular to a magnetic field. Guiding centers of all gyrating ions in the plasma are lain in the vicinity of the midplane of the plasma by the thickness. Because of these characteristics energetic ions in a sheet plasma traverse the dense plasma region only momentarily in each cyclotron gyration. As a result, the adverse effect of collisions to mass separations by ICRH can be negligible small.

In this study, we have demonstrated the ICRH of the helium or helium/hydrogen sheet plasma by the RF electrodes of two parallel plates, sandwiching the sheet plasma. Measurements of the ion temperature in the plasma were carried out by a fast scanning Faraday cup. In addition, the ion densities in the plasma were measured by an omegatron mass analyzer.

2. Experimental apparatus

A schematic diagram of an experimental apparatus TPD-SheetIV is shown in Fig.1[6]. The TPD-SheetIV device consists of the sheet plasma source, magnetic coils, RF heating part, a measurement part, end chamber, a vacuum exhaust, the Faraday cup and a omegatron mass

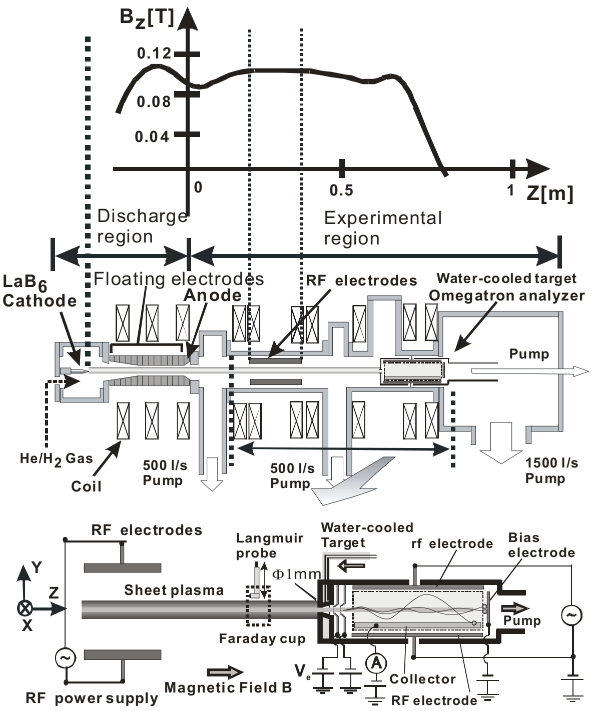

Fig.1 Schematic diagram of an experimental apparatus TPD-Sheet IV, RF power supply circuit and Omegatron mass analyzer.

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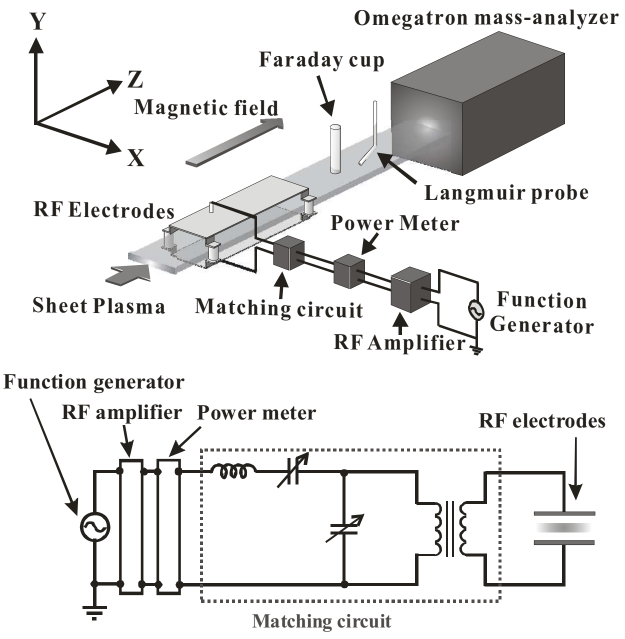

Fig.2 Schematic diagram of the measuring system and a RF power supply. $T_{i\perp}$ was measured by a fast scanning Faraday cup system.

analyzer apparatus. The sheet plasma source consists of a cathode, floating electrodes and an anode. The plasma is generated by thermal electron emission in the cathode. The floating electrodes are placed between the cathode and the anode. The floating electrodes have tapered slit, and the width and the minimum height are 40 cm and 2 mm respectively. Because of the slit the plasma which passes in the slit is compressed and be became the sheet plasma which is as thin as twice the mean ion Larmor radius. TPD-Sheet IV has 10 rectangular coils. Strengths of magnetic field of RF heating part of generated by the coils is changed from 0.08 to 0.12T. The vacuum exhaust consists of three pair of a rotary pump and a turbo molecular pump. The pressure of neutral gases of ICRH part is about 2.3×10^{-3} because of the vacuum exhaust.

Figure 1 shows a schematic diagram of the omegatron mass analyzer for ion species and electronic circuits [7]. The omegatron mass analyzer is a 5 x 5 x 15 cm consisting a stainless steal in a shielding box. The head of this analyzer, situated behind a small hole in the endplate made of tungsten, is electrically is floating and is water-cooled to allow the entire housing to be inserted into the plasma column. The inside of the omegatron mass analyzer is differentially pumped through a 2 cm diameter pumping port by a 150 l/s turbo-pump. The operation pressure inside the mass spectrometer is limited to below 10^{-2} Pa due to mean free path effects. The omegatron mass analyzer inside the shielding box consists of ion and electron repeller grids, rf cavity, and trapping end electrode. Each grid made of molybdenum is 150 line/inch and is 65% transparency molybdenum wire meshes held by a stainless steel plate. The grids can be electrically biased, allowing ion or electron repulsion. In particular, high energy electrons in the plasma are stripped away from the particle beam with a pair of electron repeller grids, which are typically dc-biased $V_r \approx$ -150V. The resulting ion beam is then slowed by an ion repeller grid and rf cavity which are dc biased to have slightly higher than the floating potential of the endplate. The end electrode can be operated as trapping ions in the rf cavity. Mass analyzer is performed by applying a radio frequency (rf) field to the top and bottom parallel plates of the omegatron and measuring the resulting current on the collector plate. Analysis of the ion trajectories in the rf field applied perpendicular to a constant uniform magnetic field shows that the ions execute spiral orbits. The peaks appear in the collector current of this spectrometer when the frequency of the applied rf electric field is equal to the ion cyclotron frequency $f_{ci} = eB/2\pi m$.

The ion temperature $T_{i\perp}$ in the range from the center to periphery regions of the sheet plasma was measured by the fast scanning Faraday cup techniques. The Faraday cup in a ceramic tube (10 mm diam.) consists of two molybdenum grids (150 mesh/inch) and a tungsten collector (5 mm diam.). This Faraday cup was located 7cm from the center of the sheet plasma. $T_{i\perp}$ can be determined from the measured ion velocity distribution function of V-I curve. Electron density, N_e, and electron temperature, T_e, were measured using a planar Langmuir probe, which were located 3 cm in front of the endplate. The probe tip (tungsten, 0.5mm in diameter) is embedded in a 1-mm-diam ceramic tube. The value of N_e and T_e can be determined from the measured electron velocity distribution function.

Figure 2 shows the schematic diagram of the measuring system and the RF applying circuit. The RF applying circuit consists of the RF power supply, a matching circuit and RF electrodes. The RF power supply consists of a function generator, a RF amplifier and a power meter. The maximum output of the RF power supply is about 500 W. The matching circuit consists of a LC circuit and BAL-UN circuit and transmits the electric power without loss. The RF electrode is two parallel plate electrodes which are 200mm in length and 60 mm in width which are faced 38 mm apart from each other. The plasma is sandwiched between the two parallel plate electrodes.

3. Experimental Results

The typical profiles of the electron density N_e, the electron temperature T_e, and the space potential V_s in the Y direction in the helium plasma are shown in fig. 3. The RF power P_{RF} is 0 W and 150 W and RF frequency f_{RF} is 500 kHz corresponding to the ion cyclotron resonance, respectively. The discharge current I_d is 25 A and the magnetic filed B is 0.105 T. Both T_e and n_e in the width direction have hill-shaped profiles with half-widths for T_e and n_e of about 6 and 5 mm for the sheet plasma, respectively. The produced sheet plasma has a steep electron temperature gradient over the narrow space of ~ 10 mm: high temperature plasma (T_e ~ 8 eV) in the central region and low temperature plasma (T_e = 3 eV) in the periphery. V_s is higher in the boundary regions than in the central region of the plasma, forming a potential well. When P_{RF} is 150 W, the V_s is more deeper although the T_e and N_e unchange.

Figure 4 shows the dependences of RF frequency of power supply f_{RF} on the ion temperature $T_{i\perp}$ at the discharge current 25 A in helium plasma. The position of the Faraday cup to the Y direction changes from 0.5 to 8.5 mm. The magnetic field B is 0.105 T and P_{RF} is applied to 150 W. The ion temperature was measured by the fast scanning Faraday cup techniques. $T_{i\perp}$has a maximum value of 500 kHz at the magnetic field strength are 0.105 T. The resonance frequencies f_{RF} is slightly higher than the ion cyclotron frequency of helium f_{ci}. This resonance frequencies f_{RF} corresponds to 1.25 f_{ci}. The shift of f_{RF} may be caused by ambipolar field which produced by the potential profile of the sheet plasma [8].

Figure 5 shows the spatial profiles of ion temperature $T_{i\perp}$ in Y-direction to the sheet plasma at the magnetic filed of 0.105 T and the discharge current of 25 A.

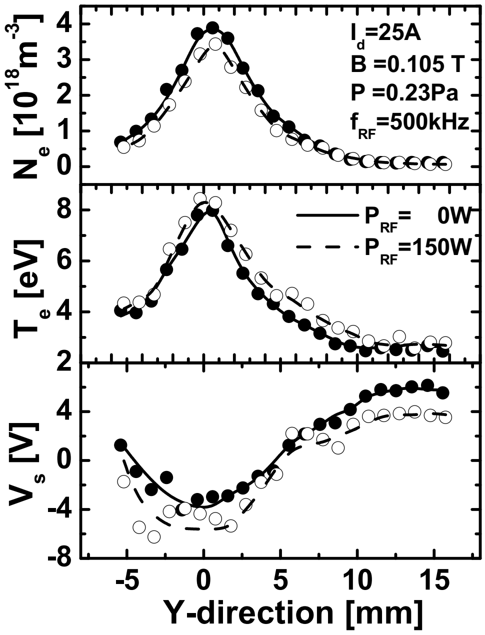

Fig.3 Spatial profiles of the electron density N_e,, the electron temperature T_e, and the space potential V_s in the width direction when RF power is off and 150 W (f_{RF} = 500 kHz).

The solid and broken lines show P_{RF} of 150 W and without RF power (P_{RF} = 0 W), respectively. RF frequency f_{RF} is 500 kHz corresponding to the ion cyclotron resonance. When P_{RF} is 0 W, the profile of $T_{i\perp}$ to the Y-direction has a broad with about 2.7 eV. When P_{RF} is 150 W, the profile of $T_{i\perp}$ has a very unique characteristics. The ion temperature in the periphery

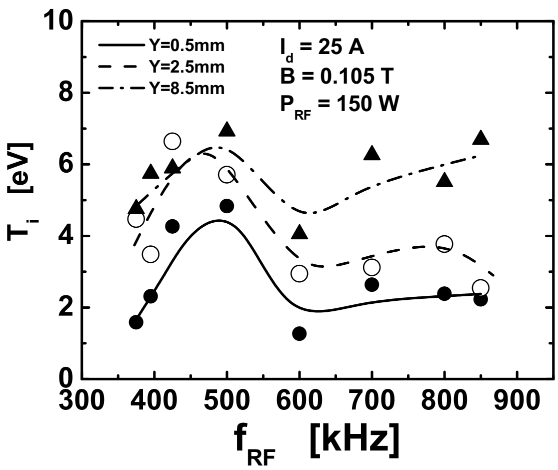

Fig.4 Dependence of the ion temperature $T_{i\perp}$, on the frequency of the RF power supply. $T_{i\perp}$ was measured by Faraday cup.

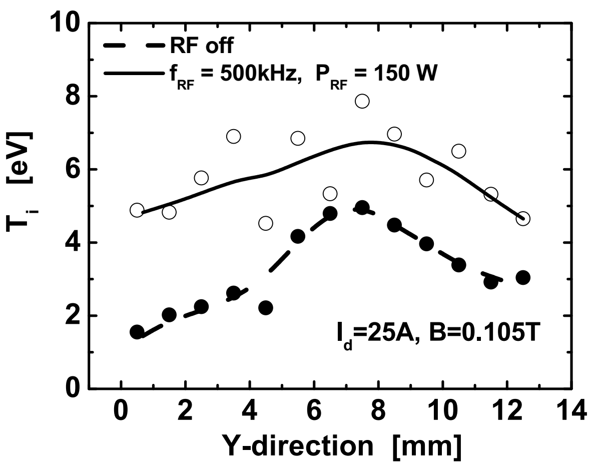

Fig.5 The ion temperature, $T_{i\perp}$, is plotted against the Y-direction. $T_{i\perp}$ in the central region of the sheet plasma was measured by spectroscopy.

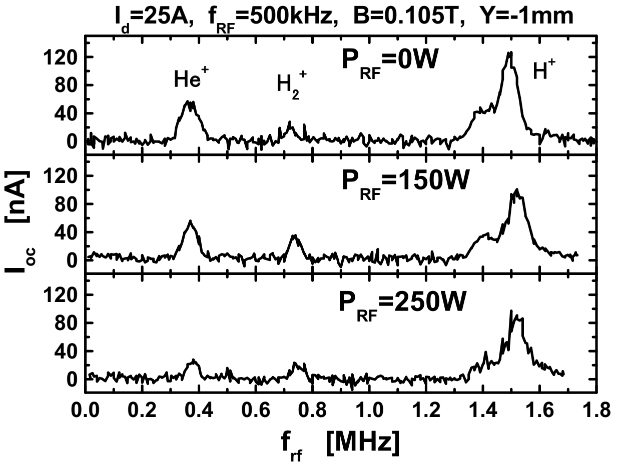

Fig.6 Typical mass spectrum of the omegatron mass analyzer at a discharge current I_d of 25 A in the helium and hydrogen mixture plasma. The applied RF frequency f_{RF} is 500 kHz corresponding to the resonance frequency of helium plasma as shown in fig.4.

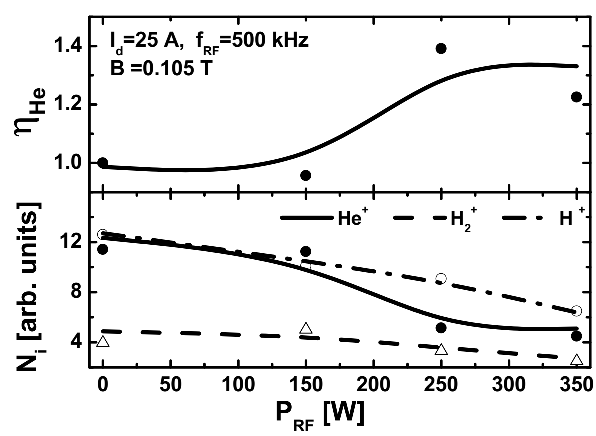

Fig.7 Dependence of the RF power P_{RF} on the ion densities N_i and the efficiency of the selective heating of He ions η_{He}. The RF frequency is 500 kHz corresponding to the resonance frequency as shown in fig.4.

region is larger than that of the center region. $T_{i\perp}$ increases to the Y-direction. In the 8.0 mm, $T_{i\perp}$ reaches to 7 eV and is comparable to the electron temperature in the central region of the sheet plasma.

In the sheet plasma, the guiding centers of all gyrating ions lie in the vicinity of the mid-plane of a plasma. Typical trajectories of resonant ions in the sheet plasma depend on the ion temperature. The frequency of an externally applied RF electric field is chosen to match the ion cyclotron frequency of the selective species to be heated. The Larmor radii of resonant ions grow secularly when they travel through the region of the RF electric field. Therefore, the ion orbits with higher energy is larger in the periphery of sheet plasma, resulting $T_{i\perp}$ rapidly increases to the width direction.

Figure 6 shows mass spectrum of the omegatron mass analyzer at a discharge current I_d of 25 A in the helium and hydrogen mixture plasma. The applied RF frequency f_{RF} is 500 kHz corresponding to the resonance frequency of helium plasma as shown in fig.4. The RF power changes from 0 to 250 W. Mass spectroscopy is performed by applying an RF field to the parallel plate of the omegatron and measuring the resulting current on the collector plate. Analysis of the ion trajectories in a uniform rf field applied perpendicular to a constant uniform magnetic field shows that the ions execute spiral orbits with a maximum excursion radius. From a typical plasma omegatron spectrum, it can be seen that the peaks correspond to H^+, H_2^+ and He^+ without RF power. The peak identification is carried out by comparing the observed peak frequencies, which is the cyclotron frequency decided by the magnetic field in the omegatron. The ion current of He^+ gradually decreases with increasing RF power.

Figure 7 shows the dependence of the RF power P_{RF} on the ion densities N_i and the efficiency of the selective heating of He ions η_{He}. The RF frequency is 500 kHz corresponding to the resonance frequency as shown in fig.4. The ion density is given by

$$N_i \propto I_i \sqrt{M_i}\ ,$$

where I_i and m_i are the ion currents of omegatron and the ion masses, respectively. The efficiency of the selective heating of He ions η_{He} is defined as

$$\eta_{He} = \frac{\alpha_0}{\alpha_{RF}}\ ,$$

where α_0 and α_{RF} are the content of the He^+ ion α without and with RF power, respectively. The content of the He^+ ion α is defined as

$$\alpha = \frac{N_{He}}{N_{He} + N_{H2} + N_H}\ ,$$

where N_{He}, N_{H2} and N_H are the density of He^+, H_2^+ and H^+, respectively. The ion densities N_i of He^+ rapidly decreases with increasing the P_{RF}, although H^+ and H_2^+ gradually decrease. As the result, η_{He} increases from 1.0 to 1.4. It is found that the selective heating of the helium ions in the sheet plasma is successful by using ICRF.

4. Conclusions

We have demonstrated the ICRH of the helium sheet plasma by two parallel plate electrodes, sandwiching the plasma. Measurements of the ion temperature of the plasma were carried out by a fast scanning Faraday cup. In addition, the ion species in the plasma were measured by the omegatron mass analyzer. The resonance frequencies f_{RF} is slightly higher than the ion cyclotron frequency of helium f_{ci}. This resonance frequencies f_{RF} corresponds to 1.25 f_{ci} of ion cyclotron frequency. The ion densities N_i of He^+ rapidly decreases with increasing the P_{RF}, although H^+ and H_2^+ gradually decrease. As the result, η_{He} increases from 1.0 to 1.4. It is found that the selective heating of the helium ions in the sheet plasma is successful by using ICRF.

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