Generation of Supersonic and Super-Alfvénic Flow Using ICRF Heating and a Magnetic Nozzle

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Fast-flowing plasmas in supersonic and super-Alfvénic regime are generated in combined experiments of ion cyclotron resonance heating (ICRH) and acceleration in a magnetic nozzle. During radio-frequency (RF) wave excitation in a fast-flowing plasma produced by a magnet-plasma-dynamic arcjet (MPDA), strong ion cyclotron heating is clearly observed. Thermal energy in the heated plasma is converted into flow energy in a diverging magnetic nozzle, where the magnetic moment μ is nearly kept constant. Plasma flow energy can be controlled by changing the input RF power and/or modifying the magnetic nozzle configuration. In a strongly diverging magnetic nozzle, an Alfvén Mach number as well as ion acoustic Mach number are more than unity, that is, supersonic and super-Alfvénic plasma flow is realized.

Keywords: supersonic plasma flow, super-Alfvénic plasma flow, ion cyclotron heating, magnetic nozzle, advanced plasma thruster

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1. Introduction

Recently, the production and control of fast-flowing plasma have became increasingly important for clarifying various MHD phenomena observed in space and fusion plasmas, for developing advanced electric propulsion systems, and for applying in various industrial studies.

In cosmic plasmas, an astrophysical jet from a fast rotating star is one of the most interesting phenomena [1]. A helical structure is often observed in the jet, and the physical mechanism of the jet formation is still under investigation. In fusion plasmas, such as those in a multiple mirror [2] and toroidal devices [3, 4], dynamics of a fast-flowing plasma in magnetic fields are important from the view point of stabilizing and improving the plasma confinement.

As for the future space exploration projects, an electric propulsion system is one of the inevitable technologies that need to be urgently developed. In an advanced space propulsion system for a manned interplanetary space flight, not only a high power density plasma thruster generating higher thrust, but also a thruster that has the capability of varying a specific impulse are required to improve propellant utilization and thrust performance.

A magneto-plasma-dynamic arcjet (MPDA) is one of the plasma sources that can generate high density plasma with high exhaust plasma velocity. It is utilized not only as one of the representative devices for electric propulsion systems but also as a supersonic plasma flow source.

Recently, intensive studies to develop an advanced space thruster named as Variable Specific Impulse Magnetoplasma Rocket (VASIMR) have been conducted for the purpose of manned Mars exploration. The thruster can control the ratio of specific impulse to thrust at constant power. The exhausting plasma flow can be controlled by a combined system of ion cyclotron heating and a magnetic nozzle [5]. A flowing plasma is heated by ion cyclotron range of frequency (ICRF) heating and thermal energy of the heated plasma is converted to flow energy in the magnetic nozzle.

We have demonstrated both ion cyclotron resonance heating and acceleration of ions in a magnetic nozzle for the first time [6]. Plasma flow was produced by an MPDA installed in the HIgh density Tohoku Plasma (HITOP) device in Tohoku University. Strong ion heating was observed and the conversion of thermal energy to flow energy in a magnetic nozzle was confirmed. This technology can be applied for the production and control of fast-flowing plasma in various applications.

In this paper, we report the experimental studies of a fast-flowing plasma heated by ICRH and accelerated by a diverging magnetic nozzle in the HITOP device, Tohoku University. We also obtained a fast-flowing plasma in the supersonic and super-Alfvénic regime at the end of a strongly diverging magnetic nozzle.

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2. Experimental Setup

Experiments were performed in the HITOP device at Tohoku University [7, 8]. A schematic of the device is shown in Fig. 1. The diameter of the cylindrical vacuum chamber is 0.8 m, and the length is 3.3 m. An external magnetic field up to 0.1 T can be produced with magnetic coils surrounding the vacuum chamber. An MPDA is installed at one end port of the HITOP, which consists of a coaxial pair of electrodes. A rod cathode made of tungsten (10 mm in diameter) and an annular anode made of molybdenum (30 mm in diameter) are used. A quasi-steady plasma was formed in 1 ms by a high power MPDA with helium as a working gas. The plasma was heated by RF waves launched by a right-handed helically-wound antenna of 160 mm in diameter, which is set at $Z = 0.6$ m downstream of the MPDA. The RF frequency f_{RF} can be varied from 0.2 to 0.5 MHz with an RF power P_{RF} up to 15 kW.

A diamagnetic coil is set at $Z = 2.3$ m to measure the plasma thermal energy. Electrostatic energy analyzers (EEAs) are set at $Z = 2.23$ m and $Z = 3.03$ m to measure ion energy distribution and ion temperature $T_{i\perp}$ and $T_{i//}$. Here, the suffix ⊥ and // indicate perpendicular and parallel components to the axial magnetic field, respectively.

In the region far downstream of the MPDA, we evaluated ion acoustic Mach number M_i using a Mach probe. The Mach probe has two plane surfaces, one of which faced the flow upstream while the other faced the flow downstream. The ion Mach number could be derived as a function of the ratio of two ion saturation current densities, J_{up} and J_{down}, The relationship between M_i and J_{up}/J_{down} was determined by the spectroscopic measurements [9,10].

3. Experimental Results

3.1 Combined experiments of ICRH and magnetic nozzle

Experiments were performed with both a magnetic-beach and diverging nozzle magnetic field configuration. In Fig. 1, the magnetic field configuration is shown with a constant B_U (= 0.1 T) at the antenna position, a variable B_D (corresponding to ion cyclotron resonance condition) at the diamagnetic coil position, and a variable B_N (corresponding to the EEA position of downstream region). Using the right-handed helically-wound antenna, RF waves were excited preferentially with an azimuthal mode number of $m = -1$ in the direction downstream of the antenna, which could couple with the cyclotron motion of plasma ions [6]. The excited RF wave in $\omega/\omega_{ci} < 1$ region propagates downward and approaches in the region of $\omega/\omega_{ci} = 1$. Here, ω_{ci} is the ion cyclotron angular frequency and is expressed as $\omega_{ci} = eB/m_i$, where e is electron charge and m_i is ion mass.

Figure 2 shows the typical waveforms of the discharge current I_d of the MPDA and the diamagnetic coil signal $W_\perp$. When radio-frequency (RF) waves were launched by a helically-wound antenna in a plasma passing through a magnetic beach configuration, strong increase in plasma thermal energy was observed, as shown in Fig. 2 (b).

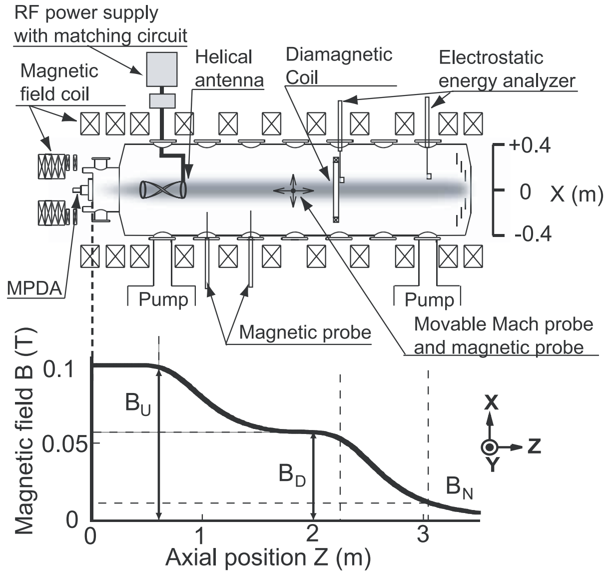

Fig. 1 Schematic of the HITOP device. Magnetic field with magnetic beach and diverging nozzle configuration is also shown.

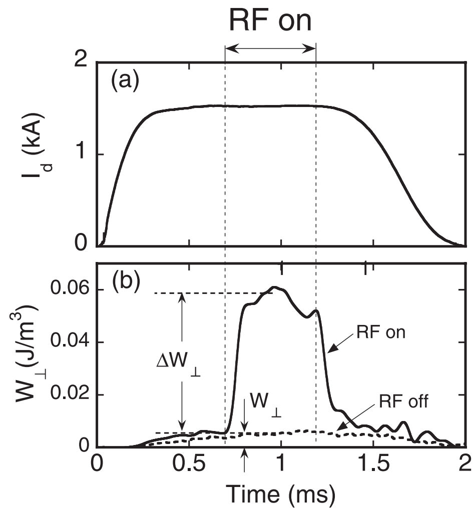

Fig. 2 Time evolutions of (a) I_d and (b) $W_\perp$. He plasma. f_{RF} = 0.24 MHz.

In order to clarify the ion cyclotron resonance heating, we varied the magnetic field B_D and measured $\Delta W_\perp$, the increment of $W_\perp$. Figure 3 indicates the dependence of $\Delta W_\perp$ on the magnetic field B_D. The magnetic field configuration was of a magnetic-beach type with a constant B_U of 0.1 T at the antenna position and a variable B_D at the diamagnetic coil position. Since the plasma conditions did not change at the antenna position, the excited wave intensity should be kept constant. The solid line indicates the B_D corresponding to $\omega/\omega_{ci} = 1$ for the excited RF frequencies. $\Delta W_\perp$ becomes large near B_D of $\omega/\omega_{ci} = 1$. It

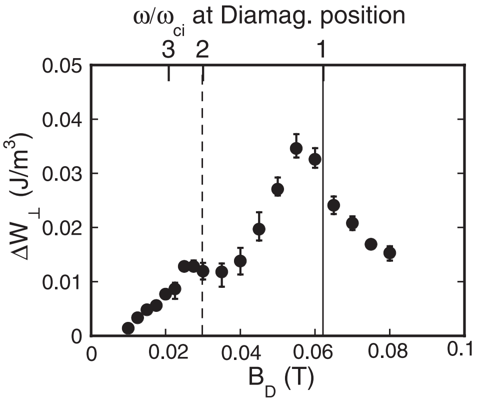

Fig. 3 Dependence of $\varDelta W_\perp$ on the downstream magnetic field B_D. He plasma. The solid and dashed lines correspond to $\omega/\omega_{ci} = 1$ and 2, respectively, for the wave frequencies of $f_{RF} = 237$ kHz.

was also observed that the peak position is slightly shifted to a lower B_D field than that corresponding to $\omega/\omega_{ci} = 1$, i.e., ω/ω_{ci} is higher than 1. This is due to the Doppler effect caused by the fast plasma flow. A small peak of increment $\varDelta W_\perp$ near $\omega/\omega_{ci} = 2$ was also observed. This is caused by the 2nd harmonic of cyclotron resonance or fundamental resonance of He^{++}ions. Further study is necessary to understand the small peak.

The plasma thermal energy was converted to flow energy in a diverging magnetic nozzle. We measured ion temperatures using the EEAs in the diverging magnetic nozzle configuration. Figure 4 shows typical EEA signals obtained before and after the nozzle with B_D (Z = 2.23 m) = 57.5 mT and B_N (Z = 3.03 m) = 17 mT. Increase in ion temperature along the perpendicular direction occurred before the magnetic nozzle. $T_{i\perp}$ increased from 3 to 27 eV with an RF input power of 15 kW.

When passing through the diverging magnetic nozzle, increase in $T_{i//}$ and decrease in $T_{i\perp}$ were clearly observed in the analyzer signals shown in Fig. 4 (b). This energy conversion occurred due to the conservation law of the magnetic moment, μ (= $W_\perp/B$).

In order to clarify the conservation of the magnetic moment, we measured the axial profiles of $T_{i\perp}$ in the diverging magnetic field. Profiles of $T_{i\perp}$ calculated by assuming μ = const. are also shown in Fig. 5. It is confirmed that $T_{i\perp}$ varied in order to keep the magnetic moment constant.

We also measured the axial profile of plasma potential V_s using electrostatic Langmuir and emissive probes. When an RF wave was excited and ion heating occurred, the potential decreased along the field line and an axial electric field was formed as shown in Fig. 6. The electric field that appeared in the magnetic nozzle accelerated the ions in the downstream direction. The formation of the electric field is probably due to the ambipolar electric field, since electrons escape from the diverging magnetic nozzle faster than ions. The

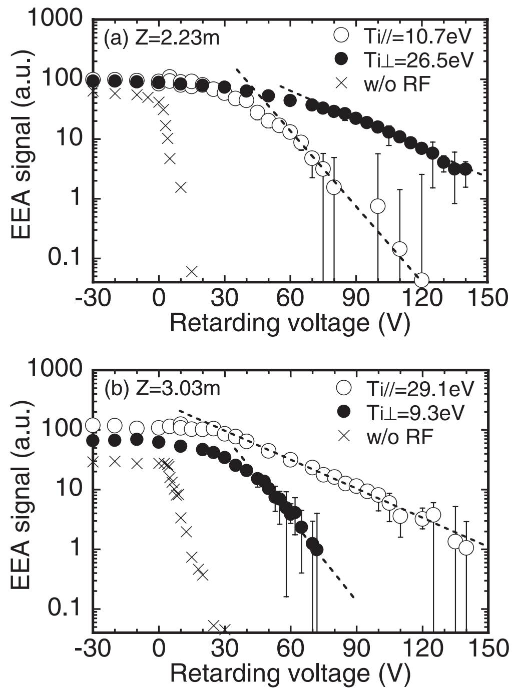

Fig. 4 Electrostatic energy analyzer signals measured at (a) Z = 2.23 m and (b) Z = 3.03 m. He plasma. P_{RF} = 13 kW, f_{RF} = 0.24 MHz, $n_e = 1.0 \times 10^{17}$ m^{-3}, B_D = 57.5 mT, and B_N = 17 mT. Open circles: $T_{i//}$, closed circles: $T_{i\perp}$, crosses: $T_{i\perp}$ without RF.

ion velocity distribution in a parallel direction to the magnetic field should be determined by conversion from the increased thermal energy and the acceleration by the electric field.

The ion acoustic Mach number M_i is one of the important parameters of an accelerated flow, which is expressed as follows:

$$M_i = \frac{U_z}{C_s} = \frac{U_z}{\sqrt{k_B\,(\gamma_e T_e + \gamma_i T_i)/m_i}} \qquad (1)$$

Here, C_s is ion acoustic wave velocity, U_z is ion flow velocity, k_B is Boltzmann constant, m_i is ion mass, and γ_i and γ_e are the specific heat ratios of the ions and electrons, respectively. The square of M_i is related to the ratio of flow energy to thermal energy of the flowing plasma. At the end of the magnetic nozzle region, this ratio is more than 3, which corresponds to $M_i > 1$, i.e., the formation of supersonic plasma flow.

The parallel energy of exhausting plasma and the ion Mach number of the plasma flow can be controlled by changing the input RF power and/or modifying the magnetic nozzle configuration.

Thrust F is yielded as a counteraction of the generation of a fast-flowing plasma flow, which is estimated as $m_i n_i S\,U_z^2$. Here, S is plasma cross section. At the exhaust region (Z = 3.03 m), n_i decreases to 3×10^{16} m^{-3} and plasma radius increases to 7.5 cm. The generated thrust is several mN and the thrust efficiency FU_z/P_{RF} is a few %.

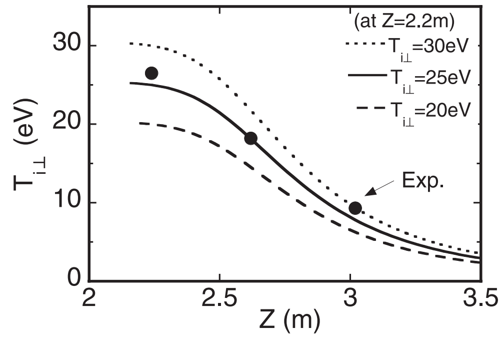

Fig. 5 Axial profile of $T_{i\perp}$ in the diverging magnetic nozzle configuration. Lines are calculated ones assuming μ = const., and $T_{i\perp}$ = 30 eV (dotted line), $T_{i\perp}$ = 25 eV (solid line), and $T_{i\perp}$ = 20 eV (dashed line). Closed circles are experimental data.

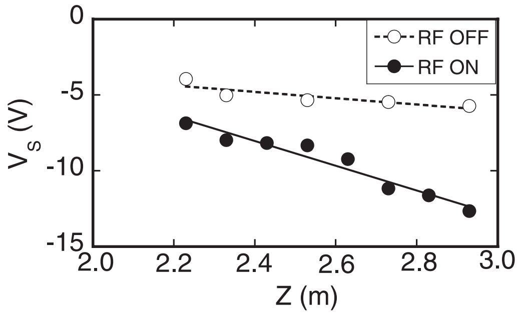

Fig. 6 Axial profile of V_s in the diverging magnetic nozzle configuration with (closed) and without (open circles) RF power.

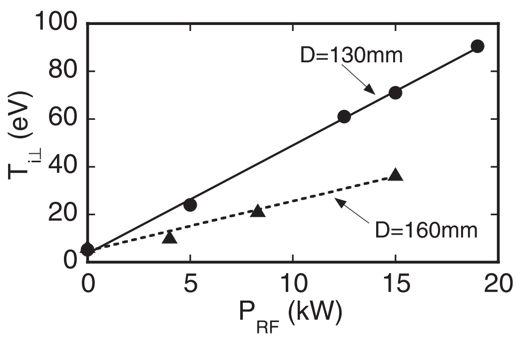

Fig. 7 Dependence of $T_{i\perp}$ measured at Z = 2.23 m on input RF power. RF waves were launched by the right helical antenna of 160 mm (closed triangles) and 130 mm (closed circles) in diameter.

One of the reasons for the low efficiency is the low value of antenna coupling with plasmas. In order to improve the antenna coupling, we performed the same experiments using an antenna with a smaller diameter of 130 mm. The heating efficiency increased more than twice as shown in Fig. 7. The exhaust energy of helium plasma was nearly 100 eV and the thrust efficiency improved. These results will be reported after further experimental studies.

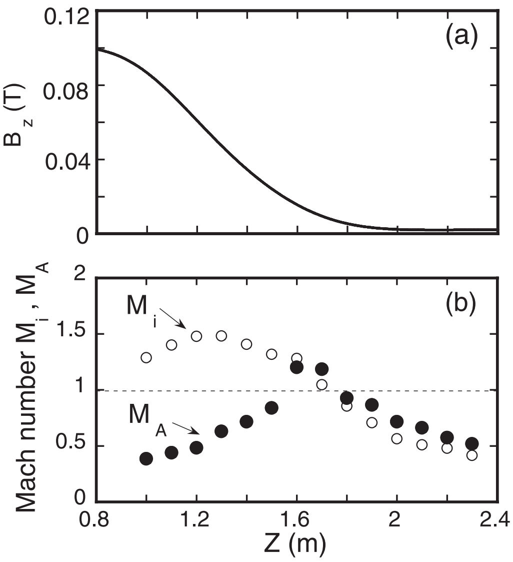

Fig. 8 Axial profile of (a) magnetic field and (b) ion Mach number M_i and Alfvén Mach number M_A in the diverging magnetic nozzle configurations.

3.2 Supersonic and super-Alfvénic plasma flow in a strongly diverging magnetic nozzle

In order to realize the super-Alfvénic flow, the plasma flow should exceed the Alfvén velocity V_A. The Alfvén Mach number M_A is defined as follows:

$$M_i = \frac{U_z}{V_A} = \frac{U_z}{B_z / \sqrt{\mu_0 n_i m_i}} \qquad (2)$$

Here, V_A is the Alfvén velocity, μ_0 is permeability, n_i is the ion density.

We measured the ion Mach number using a Mach probe and ion density using a Langmuir probe, and obtained the axial profiles of M_i and M_A in the diverging magnetic field as shown in Fig. 8. Here, no ICRF heating was applied. As shown in the figure, both M_i and M_A were more than unity, i.e., supersonic and super-Alfvénic plasma flow was realized in a laboratory plasma. The super-Alfvénic flow was controlled using the combination of ICRF heating and a magnetic nozzle.

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