Generation of supersonic and super-Alfvénic flow by 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 at 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 an ion acoustic Mach number attains to more than unity, that is, supersonic and super-Alfvénic plasma flow is realized.

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

1. Introduction

Recently, the production and control of fast-flowing plasma are of growing significance for clarifying various MHD phenomena observed in space and fusion plasmas, for developing advanced electric propulsion systems and for applying in various industrial researches.

In cosmic plasmas, astrophysical jet from a fast rotating star is one of the most interesting phenomena [1]. 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 in 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 future space exploration projects, an electric propulsion system is one of the inevitable technologies 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 which has capability of varying a specific impulse are requisite to improve propellant utilization and thrust performance.

A magneto-plasma-dynamic arcjet (MPDA) is one of the plasma sources which 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 researches to develop an advanced space thruster named as Variable Specific Impulse Magnetoplasma Rocket (VASIMR) have been performed for the purpose of manned Mars exploration. The thruster can control a ratio of specific impulse to thrust at constant power. The exhausting plasma flow can be controlled by a combined system of the ion cyclotron heating and the 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 a magnetic nozzle.

We have demonstrated for the first time both the ion cyclotron resonance heating and the acceleration of ions in a magnetic nozzle [6]. Plasma flow was produced by an MPDA installed in the HITOP (HIgh density Tohoku Plasma) 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 production and control of fast-flowing plasma in various applications.

In this paper we report 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 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 in Tohoku University [7,8]. Schematic view is shown in Fig.1. The diameter of a cylindrical vacuum chamber is 0.8m, and length is 3.3m. An external magnetic field can be produced up to 0.1T with magnetic coils surrounding around the vacuum chamber. An MPDA is installed at one end port of the HITOP, which consists of coaxial pair of electrodes. A rod cathode is made of tungsten (10mm in diameter), and an annular anode is made of molybdenum (30mm in diameter). A quasi-steady plasma was formed during 1ms 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 set at Z=0.6m downstream of the MPDA. RF frequency f_{RF} can be varied from 0.2MHz to 0.5MHz with a RF power P_{RF} up to 20kW.

Diamagnetic coil is set at Z=2.3m to measure the plasma thermal energy. Electrostatic energy analyzers (EEAs) are set at Z=2.33m and Z=3.13m 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 by a Mach probe. The Mach probe has two plane surfaces, one of which faced the flow upstream while the other faced 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 calibrated with the spectroscopic measurements [9,10]

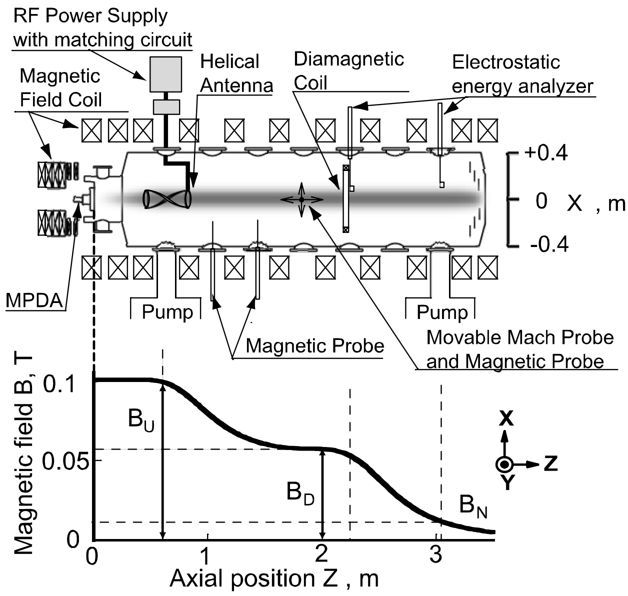

Fig.1 Schematic of the HITOP device. Magnetic field with magnetic beach and diverging nozzle configuration is also shown.

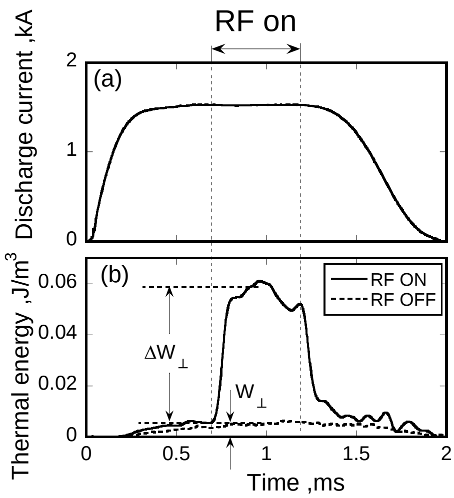

Fig.2 Time evolutions of (a) I_d and (b) $W_\perp$. He plasma. f_{RF}=0.24MHz.

3. Experimental results

3-1. Combined experiments of ICRH and a magnetic nozzle

Experiments were performed with both a magnetic-beach and a diverging nozzle magnetic field configurations. In Fig.1 the magnetic field configuration is also shown with a constant B_U (=0.1T) 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).

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 of plasma thermal energy was observed, as shown in Fig.2 (b). We have confirmed that the strong increase of $W_\perp$ occurred when the magnetic field B_D was slightly lower than that of the ion cyclotron resonance condition, ω / ω_{ci} = 1. This shift was caused by the Doppler effect. Here, ω and ω_{ci} are the angular frequency of excited RF wave and ion cyclotron motion, respectively, and ω_{ci} is expressed as $\omega_{ci} = eB/m_i$ with electron charge e and ion mass m_i.

The plasma thermal energy was converted to flow energy in a diverging magnetic nozzle. We measured ion temperatures by the EEAs in three types of magnetic nozzle configurations. Figure 3 shows typical EEA signals obtained before and after the nozzle with B_D (Z=2.33m) = 57.5mT and B_N (Z=3.13m) = 6.9mT. Strong increase of ion temperature, especially in the perpendicular direction was occurred before the magnetic

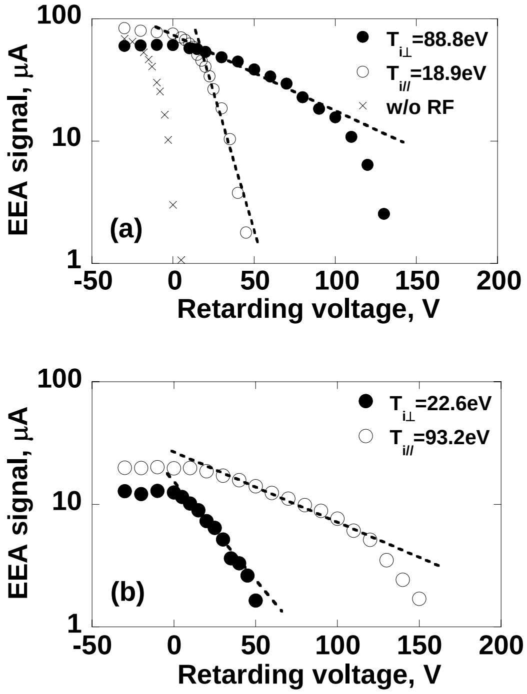

Fig. 3 Electrostatic energy analyzer signals measured at (a) Z=2.33m and (b) Z=3.13m. He plasma. P_{RF}=19kW, f_{RF}=0.24MHz, n_e=1.0×10^{17}m^{-3}, B_D=57.5mT, and B_N=6.9mT.

nozzle. $T_{i\perp}$ increased from 5eV to 89eV with the RF input power of 19kW.

The EEA signal decreased above the retarding voltage of 100V as shown in Fig.3 (a). The Larmor radius of helium ions becomes 5cm with $T_{i\perp}$ = 100eV and B = 57.5mT, which almost equals to the plasma radius. The highly-heated ions expanded to outer region and the signal measured at the center position decreased above the retarding voltage of 100V.

By passing through the diverging magnetic nozzle, increase of $T_{i//}$ and decrease of $T_{i\perp}$ were clearly observed in the analyzer signals shown in Fig.3 (b). This energy conversion was occurred due to the conservation law of the magnetic moment, μ (=$W_\perp$/B).

Figure 4 shows an axial profiles of measured $T_{i\perp}$ in the three magnetic fields. Profiles of $T_{i\perp}$ calculated by assuming μ =const. are also shown in the figure. It is confirmed that $T_{i\perp}$ varied so as to keep the magnetic moment constant but some discrepancy was observed in larger gradient of the magnetic field. It should be caused by a particle motion along a weak magnetic field.

We also measured axial profile of plasma potential V_s by an electrostatic Langmuir probe and an emissive probe. When RF wave was excited and ion heating was occurred, the potential decreased along the field line and axial electric field was formed. The electric field

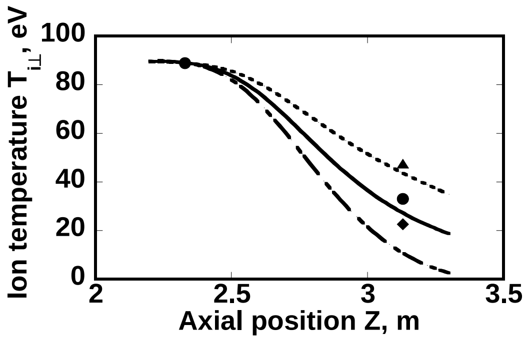

Fig. 4 Axial profile of $T_{i\perp}$ in the three magnetic nozzle configurations. Lines are calculated ones assuming μ =const. Closed triangles : B_N=28.1mT, closed circles : B_N=17.2mT, closed diamonds : B_N=6.9mT.

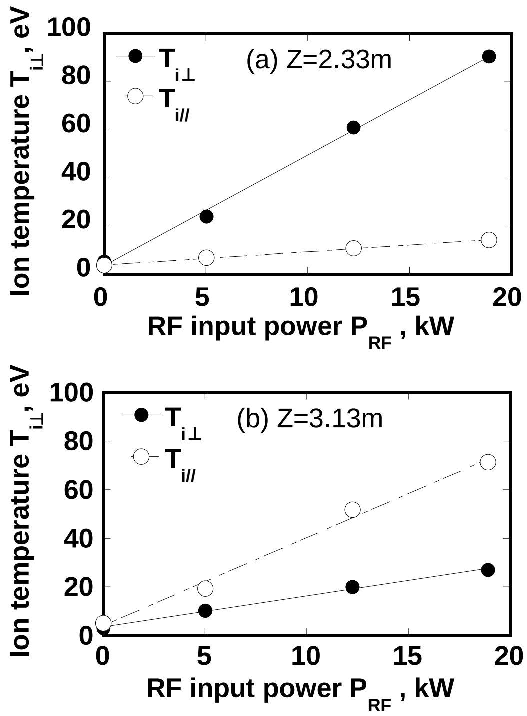

Fig. 5 Dependence of $T_{i\perp}$ (closed circles) and $T_{i//}$ (open circles) on RF input power measured at (a) Z=2.33m and (b) Z=3.13m. f_{RF}=0.24MHz, n_e=1.0×10^{17}m^{-3}, B_D=57.5mT, and B_N=17.2mT.

appeared in a magnetic nozzle accelerates ions to the downstream direction. The ion velocity distribution in parallel direction to the magnetic field was determined by the energy conversion from the increased thermal energy and the acceleration by the electric field. The formation of the electric field is probably due to the ambipolar electric field, but further study is necessary to understand this phenomena.

The ion acoustic Mach number M_i is one of the important parameters of an accelerated flow, which is defined as the following equation

$$M_{\mathrm{i}} = \frac{U_{\mathrm{z}}}{C_{\mathrm{s}}} = \frac{U_{\mathrm{z}}}{\sqrt{k_{\mathrm{B}}\left(\gamma_{\mathrm{e}}T_{\mathrm{e}} + \gamma_{\mathrm{i}}T_{\mathrm{i}}\right)/m_{\mathrm{i}}}} \qquad (1)$$

Here, C_s is the ion acoustic wave velocity, U_z is ion flow velocity, k_B is the Boltzmann constant, m_i is the 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 with the ratio of flow energy to thermal energy of the flowing plasma. At the end of the magnetic nozzle region, this ratio attained to more than 4, which corresponds to $M_i > 2$, that is supersonic plasma flow was formed.

The parallel energy of exhausting plasma can be changed by controlling the input RF power P_{RF}. Figure 5 shows dependences of $T_{i\perp}$ and $T_{i//}$ on P_{RF} measured at Z=2.33m (before the magnetic nozzle) and Z=3.13m (after the magnetic nozzle). As shown in Fig.5 (a), $T_{i\perp}$ increased linearly with the increase of P_{RF}, whereas $T_{i//}$ slightly increased with P_{RF} in the ion heating region (Z=2.33m). After the energy conversion in the magnetic nozzle, $T_{i//}$ strongly increased linearly with the increase of P_{RF} as shown in Fig.5 (b).

These experimental data clearly show that parallel energy of exhausting plasma, thus also the ion Mach number of the plasma flow, can be controlled by changing the input RF power and/or modifying the magnetic nozzle configuration.

3-2. Supersonic and super-Alfvénic plasma flow in a strongly diverging magnetic nozzle

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

$$M_{\mathrm{i}} = \frac{U_{\mathrm{z}}}{V_A} = \frac{U_{\mathrm{z}}}{B_z/\sqrt{\mu_0 n_i m_{\mathrm{i}}}} \qquad (2)$$

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

We have measured ion Mach number by a Mach probe and ion density by Langmuir probe and obtained axial profiles of M_i and M_A in the diverging magnetic field as shown in Fig.6. Here, no ICRF heating was applied. As is shown in the figure, both of M_i and M_A attained to more than unity, that is, supersonic and super-Alfvénic plasma flow was realized in a laboratory plasma. Further experiments should be necessary with the combination of ICRF heating.

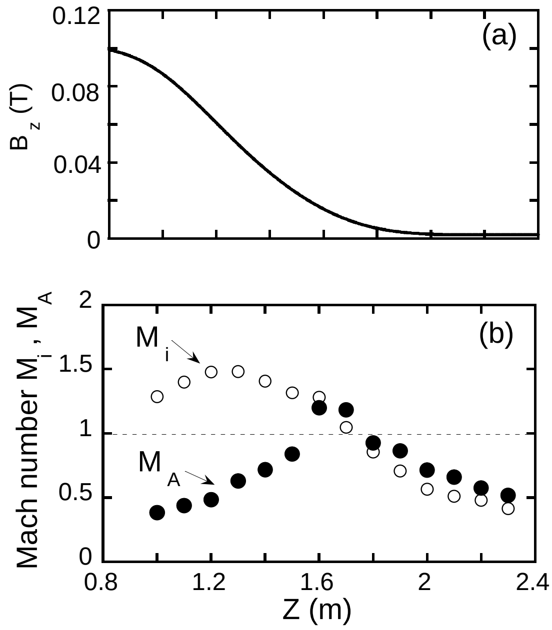

Fig. 6 Axial profile of (a) magnetic field and (b) ion Mach number M_i and Alfvén Mach number M_A in the diverging magnetic nozzle configurations.

Acknowledgments

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