Development of a 15-kW Class RF Plasma Source for VASIMR Type Space Propulsion with Magnetic Nozzle*)

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A radiofrequency (RF) plasma source was developed for space propulsion using an FET based RF inverter power supply with a power of 15 kW. The operating frequency of the RF power supply was approximately 200 kHz. By adjusting the magnetic field strength near the RF antenna to around 10 mT, we achieved high density argon plasma on the order of 10^{19} m^{-3}. The plasma passed through a region of strong magnetic field (approaching 1 T), provided by a pulsed capacitor bank for ion cyclotron resonance heating (ICRH). The plasma radius was reduced by the converging magnetic field, and the high plasma density was retained in the downstream ICRH region.

Keywords: RF plasma, plasma thruster, VASIMR, high density plasma, FET inverter, magnetic nozzle

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1. Introduction

Electric propulsion devices are powerful tools in long-term space missions because they can operate with high specific impulse. There are several kinds of electric propulsion devices, e.g., ion engines [1], Hall effect thrusters [2], and MPD arcjets [3, 4]. However, in all these devices, the electrodes become eroded by direct contact with plasmas.

A long-lived propulsion system can be realized by fully electrodeless propulsion devices, such as the Variable Specific Impulse Magnetoplasma Rocket (VASIMR) [5] and the Helicon Plasma Thruster (HPT) [6]. VASIMR utilizes a few hundred kilowatts of radiofrequency (RF) power to the ion cyclotron resonance heating section, while the HPT is operated at a few kilowatts of RF power.

The performance of both devices could be improved by RF techniques related to high density plasma production and heating, and to the physics underlying plasma expansion along the expanding magnetic nozzle. The development of a 10-kW class VASIMR type thruster should combine three main technologies; high density RF plasma production, RF ion heating, and a magnetic nozzle.

Previously, we reported high density hydrogen plasma production in a negative ion source [7–9], and ion cyclotron resonance frequency (ICRF) heating in a magnetic nozzle, which was sourced from an inverter power supply [10–12]. In the latter experiments, the ions in fast-flowing plasma were efficiently heated, increasing the perpendicular ion temperature. The supplied heat energy was finally converted into the axial flow energy in the expanding magnetic nozzle, thereby realizing a VASIMR type thruster. In a recent HPT experiment, the thruster performance was also enhanced by a convergent–divergent magnetic field, perhaps because the plasma converged near the thruster exit, rather than being lost to the radial source boundary [13]. This configuration has been already adopted in a VASIMR system [14].

To realize a table-top sized VASIMR type thruster operated with an RF power of 15 kW, we are planning a high density RF plasma source with a high power FET-based inverter RF generator. The generator operates at approximately 200 kHz. Besides the 50 Ohm matching system in RF power transmission, we have installed an inverter circuit in the RF power supply, which converts DC power to RF waves with high efficiency (exceeding 80%). This circuit can be operated at RF frequencies below 1 MHz, which is advantageous for high density plasma production because low frequencies increase the skin depth. This paper reports the characteristics of the RF source operation.

2. Experimental Setup

Figure 1 is a schematic of the compact RF plasma source used in the experiments. The source comprises a quartz tube (length = 700 mm; inner diameter = 64 mm) contiguously connected to a vacuum chamber, which is evacuated to a base pressure of 10^{-4} Pa by a rotary and turbomolecular pumping system. Argon gas is introduced from the upstream flange connected to the source tube via a mass flow controller.

The quartz tube is surrounded by magnetic coils that supply a magnetic field up to 0.7 T (see Fig. 1). The magnetic field is induced by a pulsed capacitor bank.

The inverter circuit of the RF generator is shown in

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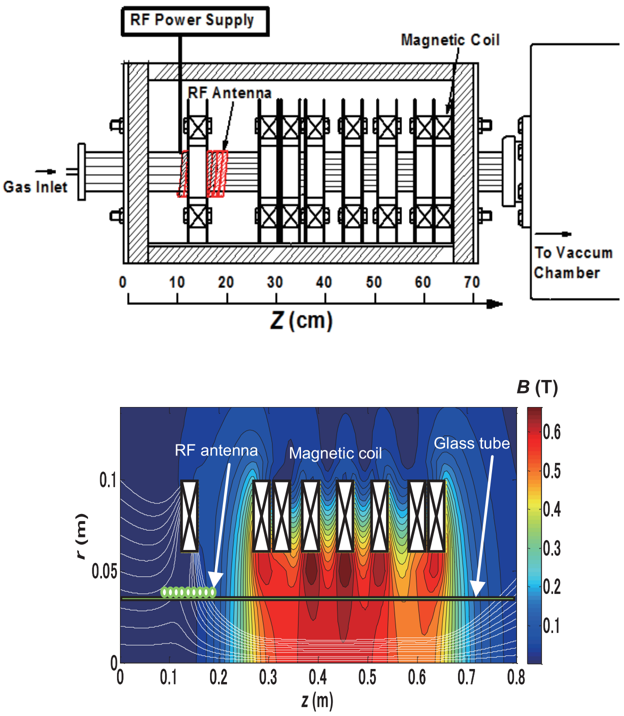

Fig. 1 (a) Schematic of the experimental device. (b) Calculated magnetic field strength (contour) and field lines (solid lines) with a magnetic coil current of 132 A.

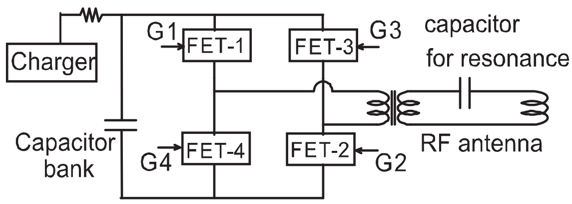

Fig. 2 A full bridge type inverter circuit with an impedance matching transformer, a matching capacitor, and an RF antenna.

Fig. 2. The operation frequency is tunable from 100 to 500 Hz by an external signal generator. A DC voltage (up to 260 V) is fed to the inverter unit, forming a full-bridge inverter circuit that switches the current on and off. The maximum current of the inverter circuit is 150 A. The total RF power delivered to the RF antenna over a short duration (8 ms) exceeds 15 kW. The RF antenna is a 9-turn loop antenna set at z = 9 - 19 cm, as shown in Fig. 1. The antenna current becomes constant after 1 - 2 ms, and the plasma reaches quasi-steady state. The output RF power is fed into the antenna via a transformer that matches the impedance of the FET inverter to the low antenna impedance. The secondary circuit forms an LC circuit combining the RF antenna and the matching capacitor. The RF frequency is set to the matching condition.

Figures 3 (a) and (b) show the waveforms of the pulsed current applied to the magnetic coils. The supplied current was nearly constant during the discharge period. Figure 4

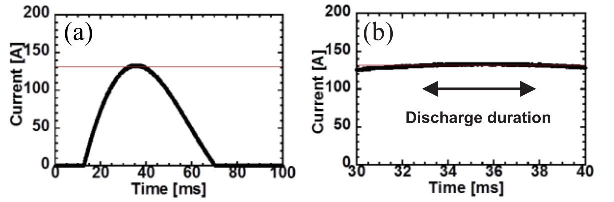

Fig. 3 (a) Waveform of magnetic coil current, and (b) enlargement of the waveform during the discharge period.

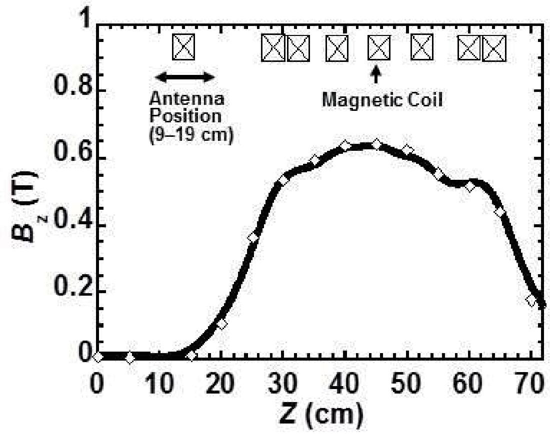

Fig. 4 An axial profile of the magnetic field with calculated (solid line) and measured (open diamonds) data.

is an axial profile of the magnetic field B_z applied in the experiments. In the downstream region (z > 40 cm), a magnetic beach configuration was formed for ICRF heating. The magnetic coil positions are also shown in the figure. The calculated curve strongly agrees with the experimental data measured by a magnetic probe (B-dot probe).

Measurements at z = 5 - 40 cm and z = 50 - 70 cm were recorded by planar Langmuir probes with a 0.9-mm diameter tungsten tip, inserted through the flanges upstream and downstream of the source, respectively. The plasma density was derived from the ion saturation current, and the electron temperature was obtained from the I–V characteristics of the probe signal, which were measured at 5 ms after the RF plasma had reached quasi-steady state.

3. Results

Figure 5 plots the plasma density and electron temperature in the RF production region (z = 3 cm) as a function of RF power $P_{\rm rf}$. The external magnetic field was applied as shown in Fig. 4. The plasma density reached 10^{19} m^{-3} at an RF frequency of nearly 200 kHz. The plasma density linearly increased with the RF power to above 10 kW, implying that the thrust provided by the source is a linearly increasing function of RF power. The electron temperature was almost constant at 5 eV and was thus independent of RF power.

Figures 6 and 7 show an axial profile of the plasma

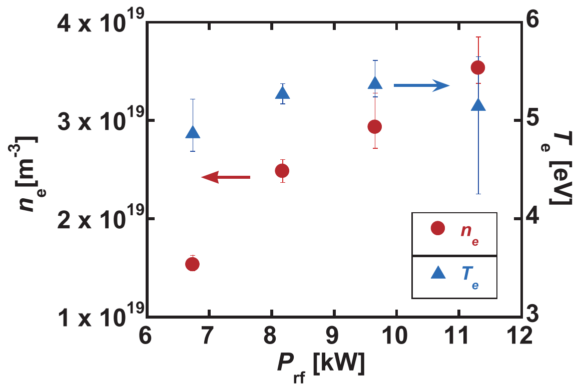

Fig. 5 Power dependence of plasma density (filled circles) and electron temperature (open triangles) measured at z = 3 cm with 1.1 Pa filling pressure of Ar. f_{rf} = 197 kHz.

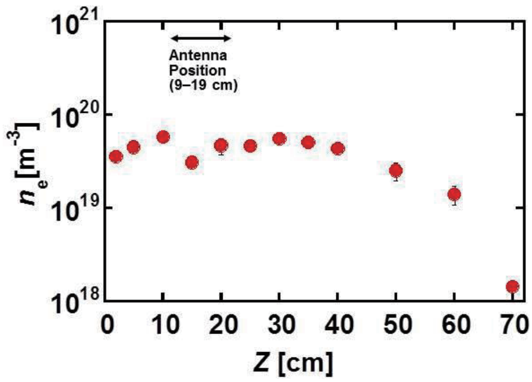

Fig. 6 Axial profile of plasma density with 2.1 Pa filling pressure of Ar. f_{rf} = 197 kHz, P_{rf} = 5.6 - 9.6 kW.

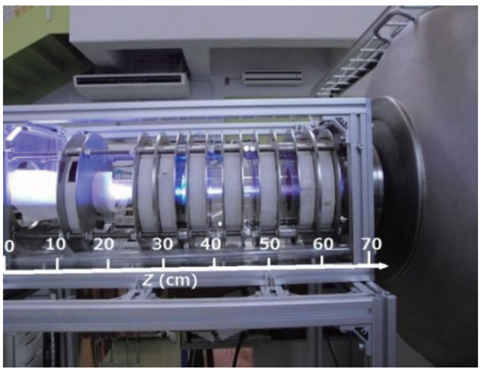

Fig. 7 Snapshot of a discharge with the magnetic field configuration of Fig. 4.

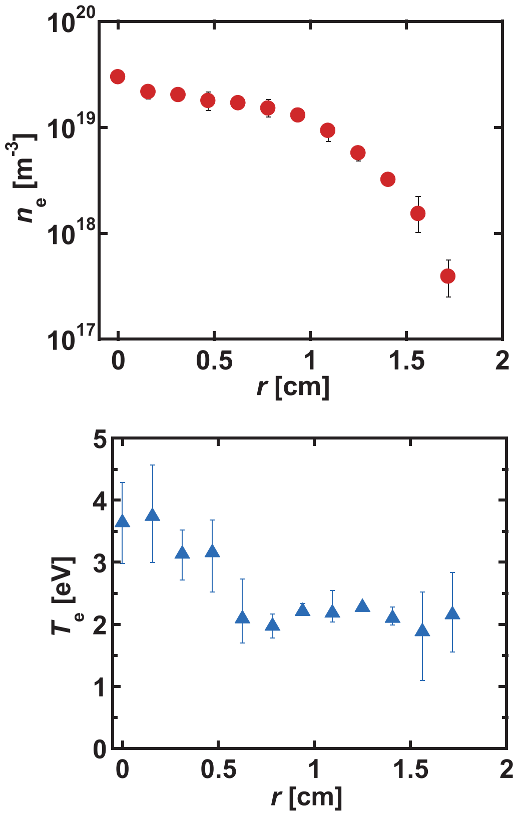

Fig. 8 Radial profiles of (a) plasma density and (b) electron temperature at z = 58 cm with 1.1 Pa filling pressure of Ar. f_{rf} = 197 kHz, P_{rf} = 12 kW.

density and a snapshot of the discharge, respectively. Experiments were performed under the Ar gas pressure of 1.1 Pa. In this configuration, a strong magnetic field (up to 0.53 T) was formed downstream (z = 40 - 60 cm), providing additional ICRF heating.

In the source region, the magnetic field intensity near the RF antenna was maintained at approximately 10 mT by a reverse coil current. 10 mT is the optimum condition for efficient plasma production with Ar gas. The strong magnetic field applied to the center region is expected to heat the ions using ICRF. Although the plasma radius was reduced by the converging magnetic field (Fig. 7), the downstream plasma density remained almost constant (exceeding 10^{19} m^{-3}) in the heating section. The strong magnetic field is considered to efficiently prevent the plasma from cross-field diffusion [13].

To reveal the spatial profiles of the plasma parameters, we measured the radial profiles of the electron density and temperature at z = 58 cm. The results are presented in Fig. 8. In this region, ICRF heating is expected to induce cyclotron resonance heating. The central electron temperature was approximately 3.5 eV, slightly lower than that in the upstream region of the source (measured at z = 3 cm; see Fig. 5). The maximum plasma density was approximately 3×10^{19} m^{-3}. The plasma radius (around 1.5 cm) agrees with that calculated by the mirror ratio, assuming that the plasma radius in the production region equals the inner radius of the source tube. Since the high density plasma remains downstream, ICRF heating is expected to improve the thruster performance. This expectation will be evaluated and reported in the near future.

4. Conclusion

We are developing an RF plasma source using an

FET inverter power supply with an RF power of 15 kW. The device is intended for a table-top sized VASIMR type thruster. An axial magnetic field up to 0.7 T was provided by magnetic coils driven by a pulsed current. By adjusting the magnetic field near the RF antenna to around 10 mT, we achieved an Ar plasma density above $10^{19}\,m^{-3}$. Furthermore, the converging magnetic field reduced the plasma radius, while retaining the high plasma density in the downstream ICRF region. The additional ICRF heating is expected to improve the thruster performance.

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