# A Compact Permanent-Magnet Helicon Thruster

Francis F. Chen

***Abstract*— A small helicon source using a permanent magnet has been tested for possible application as a spacecraft thruster. Ion energy distributions measured with a retarding-field ion analyzer show that ions are ejected with energies of ∼5 $KT_e$, in agreement with theory. The specific impulse can be increased by applying a positive bias to the endplate of the discharge.**

***Index Terms*— Ambipolar thruster, compact thruster, helicon, helicon thruster, permanent-magnet helicons, spacecraft thruster, thrusters**

## I. Discharge Configuration

NORMAL spacecraft thrusters eject a fast ion beam, which has to be neutralized by electrons from an auxiliary source to prevent the spacecraft from charging up negatively. This is not necessary in ambipolar thrusters, which eject neutral plasma. Helicon discharges require less power to generate a given plasma density than other ambipolar sources, but they require a dc magnetic field **B**. This obstacle has been overcome by the use [1], [2] of vertically polarized annular magnets located away from the discharge, as shown in Fig. 1. As seen in Fig. 2, the $B$-field below the magnet reaches a stagnation point not far from the magnet; the discharge is located below this, where the field is quite uniform and nearly vertical. In previous experiments, specially designed neodymium (NdFeB) magnets were used, but that work showed that $B$-fields greater than ∼60 G (6 mT) yielded negligible improvement in plasma density [3]. As a result, a smaller system using a commercially available magnet was designed and tested. The magnet shown in Fig. 1 is of 2-in ID, 4-in OD, and 0.5-in thickness. The discharge tube is of 2-in ID and 2-in height, topped by a grounded aluminum plate (to reflect the back wave). The discharge runs in argon from 0.5 to 60 mTorr with 50 to 2000 W of 27.12-MHz RF. The single loop antenna is located near the exit to minimize plasma loss to the walls. Maximum density inside the tube is $\approx 5 \times 10^{12}$ cm$^{-3}$. Fig. 3 shows $|B_z|$ *versus*. $z$ and the location of the discharge for $|B| \approx 60$ G.

## II. Measurements

As plasma exits the source, the electron density decreases, following the diverging field lines. Since the electrons are Maxwellian, the plasma potential also decreases. Thus, there is an electric field that accelerates the ions along **B**. Using a retarding-field ion analyzer (RFIA) made by Impedans, Ltd. of Ireland, we have measured the ion energy distribution function

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The author is with the University of California at Los Angeles, Los Angeles, CA 90024 USA (e-mail: ffchen@ee.ucla.edu).

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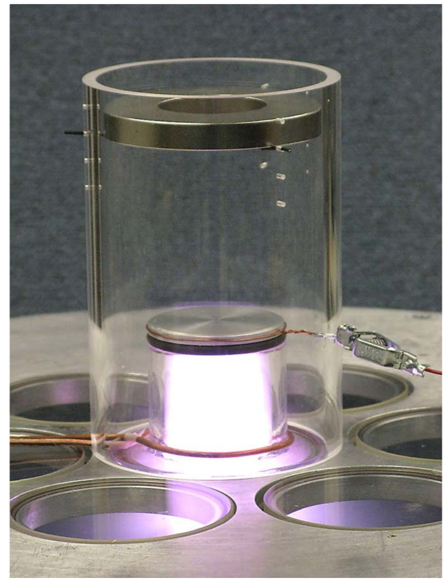

Fig. 1. Argon helicon discharge with a permanent magnet.

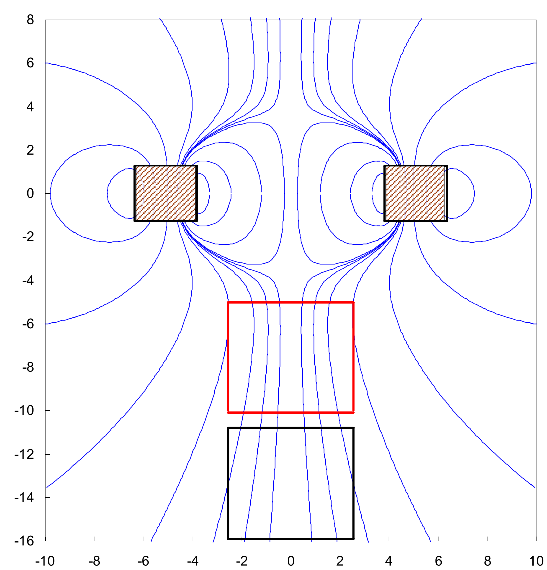


Fig. 2. Small squares: $B$-lines around a large annular magnet. Large squares: two possible positions of the discharge tube. The $B$-field can be varied by moving the magnet vertically relative to the discharge.

at various positions below the source. A sample power scan, at 5 mTorr, is shown in Fig. 4. It is seen that the ion energy peaks at ∼12–14 eV. A normal sheath drop at the wall of an argon discharge is ∼5 $KT_e$, or ≈10 eV for $KT_e \approx 2$ eV [3]. Thus, the ion acceleration has the approximate expected magnitude. The apparent occurrence of ions at negative voltages is due to the RF filtering circuit and collisions with neutrals before reaching the sensor. Fig. 5 shows that higher ion velocities can be obtained at lower pressures.

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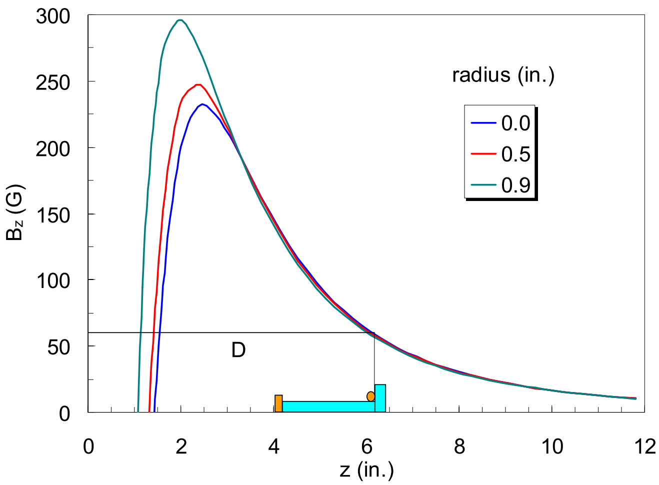


Fig. 3. *B*-field in the region below the stagnation point (at three radial positions), and the location of the discharge tube when the antenna is at 60 G.

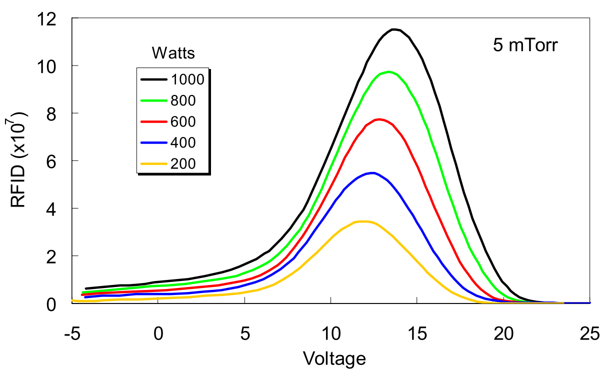


Fig. 4. RFIDs versus voltage on the collector plate relative to ground at 5 mTorr and various RF powers.

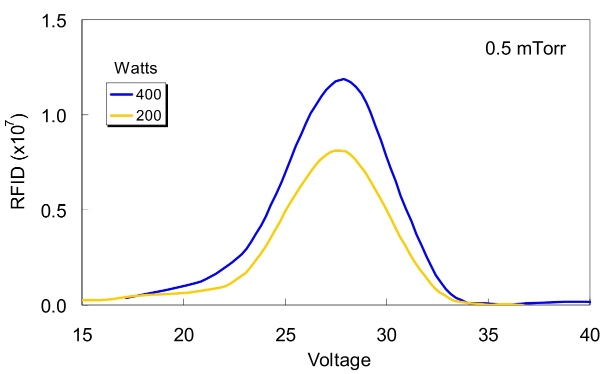


Fig. 5. RFIDs versus voltage relative to ground at 0.5 mTorr.

Fig. 6 shows how the RFIA is mounted in the experimental chamber. The RFIA is a disk 4-in in diameter and 1/4-in thick, encased in oxidized aluminum. Since it is an RF conductor, it affects the discharge in its uppermost positions by becoming a second endplate for the helicon waves. More importantly, it blocks the position where the double-layer studied in [4] would normally occur (Fig. 7). Nonetheless, though a sudden potential drop cannot be seen, the ion acceleration is still there and can be seen downstream.

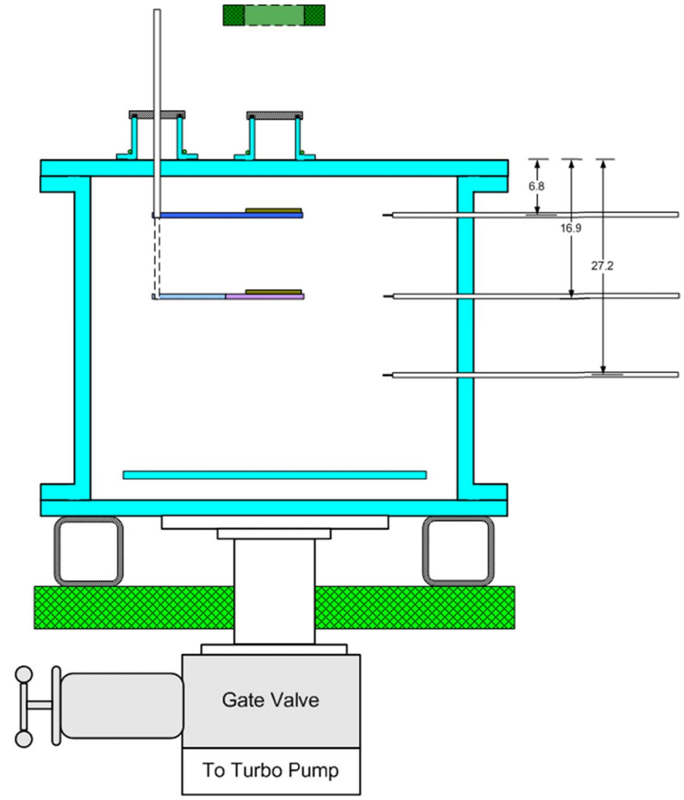


Fig. 6. Schematic of the experimental chamber showing locations of three probe ports and the sliding mount for the RFIA sensor.

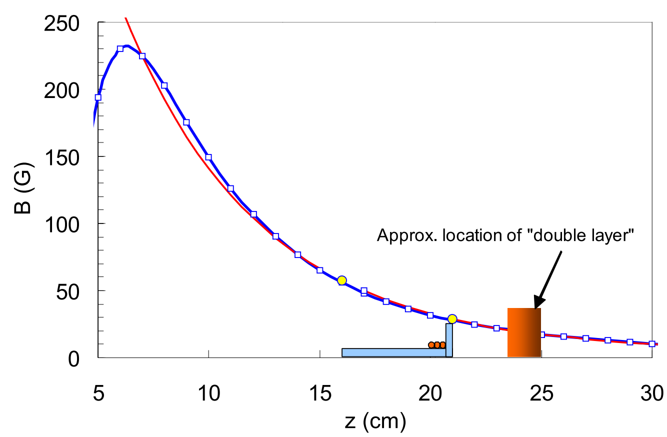


Fig. 7. Location where a double-layer would occur in the absence of the RFIA sensor. The location is not a single point because *B* is not uniform in the discharge.

The retarding-field ion distributions (RFIDs) at Port 2, 16.9-cm below the source, are shown in Fig. 8 for various RF powers. It is seen that the ion flux increases with power, but the energy peak does not move much. These results show a much smaller ion acceleration than was reported in [5] at higher *B*-fields and lower pressures.

## III. Application to Thrusters

At our normal operating pressure of 15 mTorr, Fig. 8 shows that the peak ion energy is only ~10 eV; but at pressures in thrusters, the ion energy is much larger, as seen in Fig. 5. The question is whether this energy can be increased even

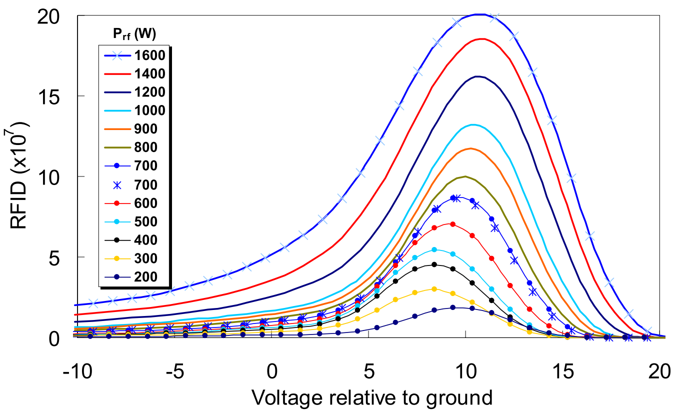


Fig. 8. Downstream ion distributions at Port 2 versus RF power at 15 mTorr. Two curves at 700 W show reproducibility at beginning and end of run.

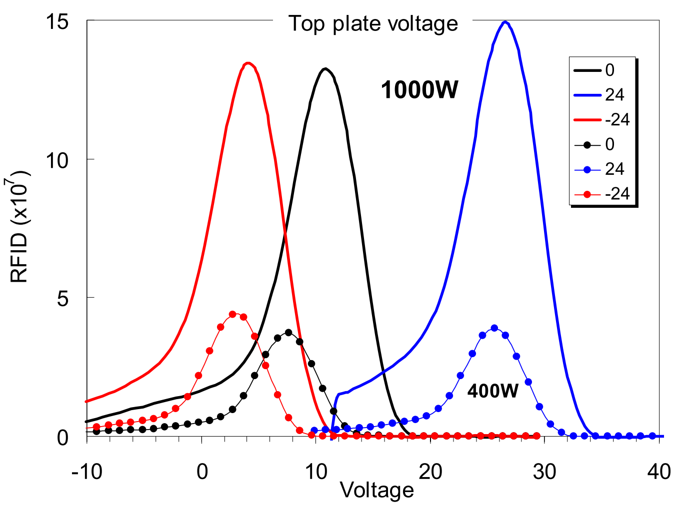


Fig. 9. Ion distributions at Port 2 with at 1000 and 400 W with top plate voltages of 0 V (black curves), −24 V (red curves), and +24 V (blue curves).

further by biasing the top plate of the discharge relative to the spacecraft ground. We have tested this at 15 mTorr, and Fig. 9 shows that it is indeed possible. Because of the severe RF environment, an electronic power supply can be used only with filtering by large electrolytic capacitors. Instead, we used two 12-V lead-acid batteries in series to supply ±24 V to the top plate. The peak ion energy is indeed altered, but the shift is less than the applied voltage, being only 15 and −7 V, respectively. Nonetheless, the thrust can, in principle, be increased arbitrarily by applying a dc voltage, as is done in existing ion and Hall thrusters. Compared with these, a helicon thruster can provide a much denser ion beam with automatic electron neutralization.

Thrusters are characterized by their specific impulse $I_{sp}$, among other criteria

$$I_{sp} \equiv \frac{v_{ex}}{g}$$

where $v_{ex}$ is the exhaust velocity of the ions, and $g$ is the gravitational constant 9.8 m/s$^2$. Fig. 5 shows that the ion distribution peaks above 30 eV at low pressures. This energy corresponds to an $I_{sp}$ of ∼1200. To obtain an $I_{sp}$ of over 3000, one needs to increase the ion energy to 200 eV or so, which can easily be done with a positive top plate bias. The current drawn by a biased top plate is only at the milliamp level; apparently, the sheath there changes so that a large electron current is not necessary to provide a helicon equilibrium. This preliminary experiment suggests the possibility of developing a permanent-magnet helicon thruster.

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Authors' photographs and biographies not available at the time of publication.