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Recent Work on an RF Ion Thruster

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RECENT WORK ON AN rf ION THRUSTER

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ABSTRACT

Although extensive research efforts have been devoted to the development and improvement of the electron bombardment dc ion thruster over the past 20 years, relatively little work has been done in this country on high frequency plasma discharge ion thrusters for spacecraft propulsion. Early research and development of the radio frequency (rf) ion thruster was carried out in Germany by H. W. Loeb.[1] The rf ion thruster differed from the electron bombardment type thruster by using an electrodeless, self-sustaining rf discharge. The discharge vessel was made of insulating material, and was positioned inside the induction coil of a rf transmitter. After careful optimizations, the rf thruster has demonstrated high performance. Other investigators have experimented with plasma discharge produced by an rf coupler immersed within the plasma.

An experimental investigation of an rf ion thruster using an immersed coupler in an argon discharge is reported in this paper. The conical coil, used to couple rf power into the discharge, is placed inside the discharge vessel. The discharge was self-sustained by 100-150 MHz rf power at low environmental pressures ($\sim 10^{-5}$ torr). The ion extraction was accomplished by conventional accelerator grid optics from an unoptimized 8 cm diameter ion thruster.

The ionization mechanism of the rf ion thruster differs from the dc thruster in many respects. In the rf discharge, ionization is produced by random oscillatory motion of the electrons. Since the field reverses direction periodically, the charges are not continuously swept out of the discharge volume between the electrodes. Because there is no cathode, problems which may be associated with low work function emitters are eliminated. Also since bombardment of the electrodes by energetic particles is reduced, the prevailing temperature of the rf ion thruster is lower. This report presents the early results of this investigation, and no attempts at optimization or detailed diagnostic measurements have been made. Preliminary results have yielded ion production cost of 525 watt/beam amp. at an input power of 40 watts.

INTRODUCTION

A high frequency plasma discharge may be an attractive alternate ion source for electrostatic ion thrusters. Compared to dc discharges, the absence of the thermionic type cathode and conventional anode reduces the power supply requirements and losses associated with these electrodes. Initial heating of the cathode and inadvertent overheating of low work function surfaces are also avoided. Based on these considerations, an exploratory effort into high frequency ion generation for ion thrusters has been undertaken at the NASA Lewis Research Center.

High frequency plasma generation has been studied since the turn of the century. Early experiments focused on basic properties and nonlinear phenomena of high frequency discharges.[1-3] Recent efforts have led to practical application in plasma chemistry,[4] lasers[5] and space propulsion.[6]

Early research and development of the radio frequency (rf) ion thruster was performed in Germany by Loeb.[6] With optimization, the rf thruster (RIT10) has demonstrated an ion production cost of 350 eV/ion using a mercury propellant. This is about 50 percent higher than the ion production cost of present mercury thrusters which use dc discharges.[7] One of the reported disadvantages of the RIT thruster, however, was that "skin effect" in the dense discharge plasma prevented the penetration of the rf fields from an externally located induction coil. The "skin effect" encountered in this inductive coupling can be avoided by using a suitable coupler immersed within the plasma. High frequency discharges using a Lisitano coil[8] and variation of this concept have been reported.[9]

This paper presents some preliminary results of an rf ion thruster using an immersed coupler in an argon discharge. Conventional ion accelerator optics were used to extract an ion beam. Operation of an unoptimized thruster over a range of input power, propellant flow rate, frequency and magnetic field strength is described. Lifetime and overall efficiency factors have not been investigated extensively as yet. The results obtained thus far primarily established the feasibility of this approach and the potential for future improvements.

BASIC CONCEPTS

The ionization mechanism of the high frequency ion thruster differs from the dc thruster in many respects. Ionization in the high frequency discharge is produced by random oscillating electrons which collide with neutral particles. Energy is imparted to the electrons by the rf field. Instead of being continuously swept out of the discharge volume between electrodes as in a dc discharge, the oscillating electrons are lost through diffusion, recombination and attachment processes. For a diffusion-controlled high frequency discharge, the time average power absorbed per unit volume in a cold ($T_i = T_e = 0$), high frequency plasma can be expressed as[10]

$$P_{abs}(r) = \frac{N_0(r)e^2}{m_e \nu_e} \frac{\nu_e^2}{(\nu_e^2 + \omega^2)} \frac{E_0^2(r)}{2} \qquad (1)$$

where

$N_0(r)$	electron density, m^{-3}
e	electronic charge, coulombs
ω	excitation frequency, radian per second
$E_0(r)$	spatial electric field, volts/meter
ν_e	effective electron-neutral collison frequency
T_i	ion temperature, eV
T_e	electron temperature, eV

Equation (1) states that the amount of microwave power absorbed by the plasma depends on the exciting frequency, electron density and electron energy distribution. As reported in reference 11, the high frequency plasma was seen to show preferential absorption of microwave energy at resonance and a tendency to stay in a resonance state. For a cold, high frequency plasma of infinite extent, resonances occur when $\omega \sim \omega_e$, where ω_e is the electron plasma frequency. For bounded plasmas, the resonance depends upon the geometry and boundary and plasma conditions. Because of low reflected power at resonance, a resonantly sustained plasma can be maintained with relatively low rf voltages.

Efficient coupling of microwave power into the plasma requires the plasma-microwave circuit to be in resonance. In the design of rf ion thrusters, both plasma and circuit parameters, such as gas pressure, thruster shape and size, exciting frequency and type of coupler must be considered. For low frequency (MHz), an antenna type coupler can provide acceptable impedance matching with the external microwave circuit. For high frequency (GHz), a tunable microwave cavity or waveguide structure might be a better choice.[8,12-14]

Magnetic field confinement has been used to enhance the efficiency of an electron bombardment type ion thruster. In his paper,[6] Loeb also mentioned that the "skin effect" can be partly removed by a weak perpendicular constant magnetic field. It is well known that a constant magnetic field superimposed on a high frequency discharge caused energy resonance (magnetic cyclotron resonance) and reduced diffusion loss of charged particles in the direction perpendicular to the magnetic field.[15] These two phenomena have profound effects on energy coupling and ion generation in a high frequency discharge as exhibited in the experimental results.

APPARATUS AND PROCEDURES

Two different ion source configurations shown in figure 1 were investigated. Configuration (1), figure 1(a), consisted of a constant diameter cylindrical discharge housing 15 cm long with an inner diameter of 6.5 cm. The rf power was coupled into the gaseous discharge through a conical coil coupler which was held in position by a thick ceramic tube 7 cm long. The ceramic tube fitted coaxially within a copper body. On the downstream end of the body was a copper disk with drilled holes to direct propellant flow toward the coil coupler. The body with coupler in place fitted to the housing to complete the assembly. The conical coil was connected to a coaxial cable transmission line via a modified type N connector mounted on the upstream end of the body. Figure 1(a) shows the components of configuration (1). To study the configurational effects (size, shape) on ion generation, a second configuration (2) utilizing the same body but a different discharge housing and conical coil coupler, was tested. These components are shown in figure 1(b). The discharge housing was essentially a truncated cone 10 cm long with diameters of 5.3 and 7.5 cm. A conical coil coupler was 5.5 cm long with diameters of 2.5 and 6.0 cm.

A schematic diagram of the experimental setup is shown in figure 2. Argon was introduced into the ion source through a length of rubber hose which allowed electrical isolation of the source from ground potential. The gas flow was regulated with a variable leak valve, and was measured with a flow meter. In most of the tests, the flow rate was kept at 290 milliamperes equivalent of singly charged Argon ions. At this flow rate, the configurations operated stably over a broad frequency range.

The rf circuit consisted of a variable frequency (1-520 MHz) signal generator connected to a rf power amplifier. The maximum output rating from the power amplifier was about 500 watts. An on-line power meter was inserted between the power amplifier and the rf ion source to measure the incident and reflector powers. Because a 'floating' system is required for effective ion extraction, the whole rf power circuit was isolated from ground across a 115 volt a.c. line transformer.

Three separately wound electromagnet coils of 125 turns each (see fig. 2) were placed circumferentially around the ion source. These coils could produce a variable, axial magnetic field of 0 to 150 gauss. The ion source was made into a thruster by mounting a set of conventional 8 cm diameter ion accelerator optics to the source. The ion beam was extracted by biasing the screen (upstream) grid to a positive 1200 volts, and the accelerator grid to a negative 250 volts. A hot wire tantalum neutralizer coated with barium carbonate was used to provide beam neutralizing electrons.

Tests with the ion thruster were carried out in a vacuum tank at environmental pressures of about 10^{-5} Torr (1.3×10^{-3} Pascals). At the start of the experiment, the hot wire neutralizer was slowly heated up with 70 watts of power. Then, argon was fed into the ion thruster. At a pressure of approximately 10^{-4} Torr (1.3×10^{-2} Pascals), gas breakdown occurred with an incident rf power of about 30 watts. To obtain beam currents, the extraction grids were biased to the specified voltages. The current, J_A (see fig. 2) flowing through the accelerator grid became very small, and the current, J_B, through the beam power supply was approximately equal to the extracted beam current. Next, the variable dc magnetic field was adjusted individually for maximum beam current. A range of frequency from 40 to 160 MHz at an incident power from 20 to 100 watts was covered. Argon flow rate was varied from approximately 100 to 300 milliamperes equivalent of A_r^+.

RESULTS AND DISCUSSION

Experimental data for the ion source (Configuration (1)) were obtained for an incident power of 40 watts at a flow rate of 290 milliamperes equivalent of A_r^+. Figure 3(a) shows the variation of optimum magnetic coil currents as a function of exciting frequency. The variation of the exciting frequency versus reflected power and beam current are shown in figures 3(b) and (c), respectively. These results were optimized by varying the magnetic coil currents. Similar experimental results are shown in figure 4 for the conical shaped discharge vessel (Configuration (2)). The optimized magnet currents (fig. 4(a)) at each frequency were the individual coil currents which obtained the maximum beam current. The frequency dependence of the reflected power and the beam current demonstrates the resonance nature of the rf discharge. From figures 4(b) and (c), it appears that the power transferred to the plasma was near optimum at a frequency of about 154 MHz. At this frequency, the reflected power was less than 5 percent of the incident power. Of the two configurations experimented, Configuration (2) provided a better impedance matching in coupling rf power into the plasma. By comparing figures 3(c) and 4(c), the optimum beam current for Configuration (2) was about 20 percent higher than that for Configuration (1). The remainder of this discussion, therefore, will be confired to results obtained with Configuration (2).

The variable dc magnetic field was observed to influence significantly the output of beam current. At 154 MHz, the effects of the magnetic coil currents on the reflected power and the beam current are shown in figures 5(a) and (b), respectively, for an incident power of 40 watts. In each case, the beam current was first optimized by varying the individual magnetic coil currents. Then, the effects on the reflected power and the beam current were observed by holding two magnetic coil currents constant and varying the current in the third coil. Results indicate that the beam current could be increased over 50 percent with adjustment of the magnetic field. It appears from figure 5(b) that the electromagnetic current coil, J_3 (see fig. 2) predominated over J_1 and J_2 in ion generation as demonstrated in the large variation of beam current with J_3.

The absorbed power versus the reflected power and the beam current are shown in figures 6(a) and (b), respectively. These data were taken with optimum magnetic coil currents and at frequency of 154 MHz. Figure 6(b) shows that the beam current increased with absorbed power.

Figure 7 shows the ion production cost versus the mass utilization efficiency at a frequency of 154 MHz. These performance data were obtained by varying the input power while holding the flow rate constant and vice versa. The ion production cost for this unoptimized thruster is about 525 watts/beam amp. at environmental pressures of 10^{-5} Torr (1.3×10^{-3} Pascals). The parameter, eV/ion, is a widely accepted figure of merit for discharge performance of electrostatic ion thrusters. It is calculated by dividing the net ionization chamber discharge power by the output ion beam current. In this paper, ion production cost is defined as the absorbed power divided by the output beam current to give unit of watts/beam ampere.

Sputtering was observed inside the discharge tube at incident power over 40 watts. By inserting a glass tube between the conical coil and the inner tube wall, a thin film of metallic deposit was seen on the glass tube surface. The sputtering phenomena can be explained as a result of higher effective electric field and electron temperature in the high frequency discharge. The presence of the intense rf electric field in the sheath region may result in higher ionization frequency and electron temperature to maintain the discharge.[16,17]

CONCLUSIONS

An experimental study of an rf thruster using a conical coil ionizer in an argon discharge has been undertaken. Two discharge chamber designs were studied. Of the two a conical configuration provided a significantly better coupling to the plasma discharge.

Solenoidal magnetic fields and driving frequencies were varied to match the plasma impedance and maximize rf power transfer. Coupling was achieved at a typical power level of 40 watts with less than 2 watts of reflected power at a frequency of about 150 MHz. Power absorption as high as 95 watts was demonstrated though most of the investigation was at 40 watts. No difficulties were encountered using the 8 cm ion optics to extract ions.

Preliminary results have yielded an ion production cost of 525 watt/beam amp. at an input power of 40 watts. These results indicate only the feasibility of the rf thruster concept and not the optimum performance of the system. It is believed that improvements can be made with other antenna designs and with different ionization methods, such as a metal traveling wave structure[8,12] or a microwave cavity.[13,14]

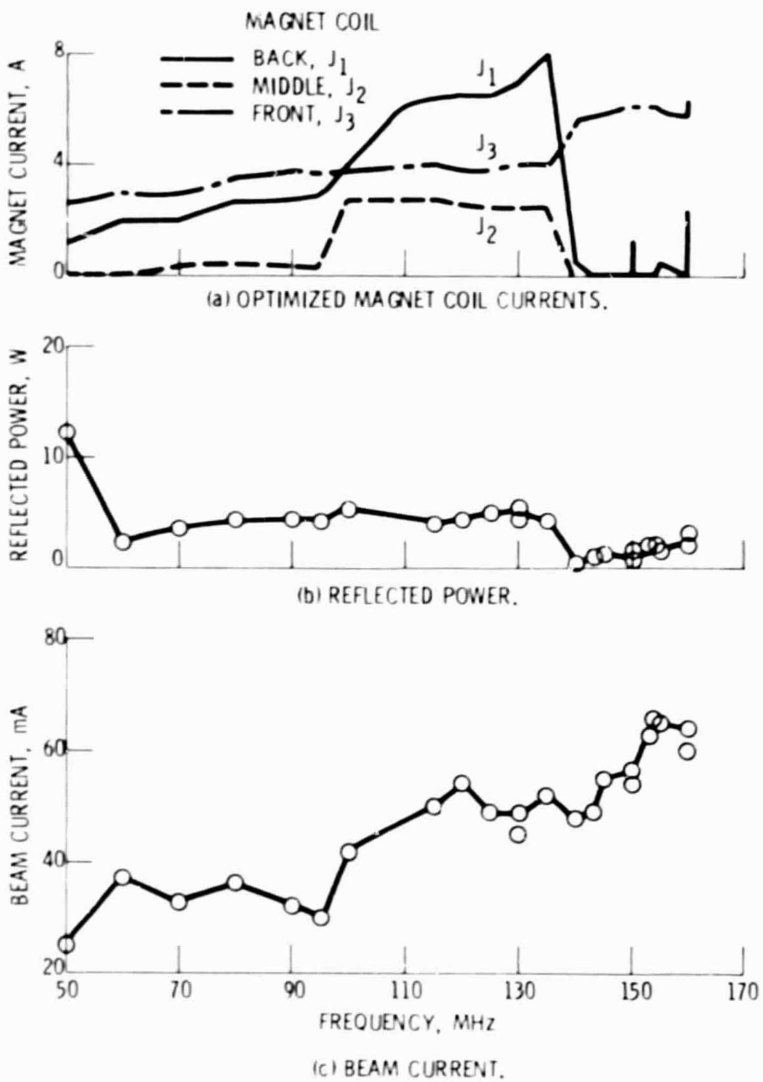

Figure 4. - Characteristics of a divergent discharge chamber (configuration 2) incident power, 40 W; argon flow rate, 290 mA Ar^+.

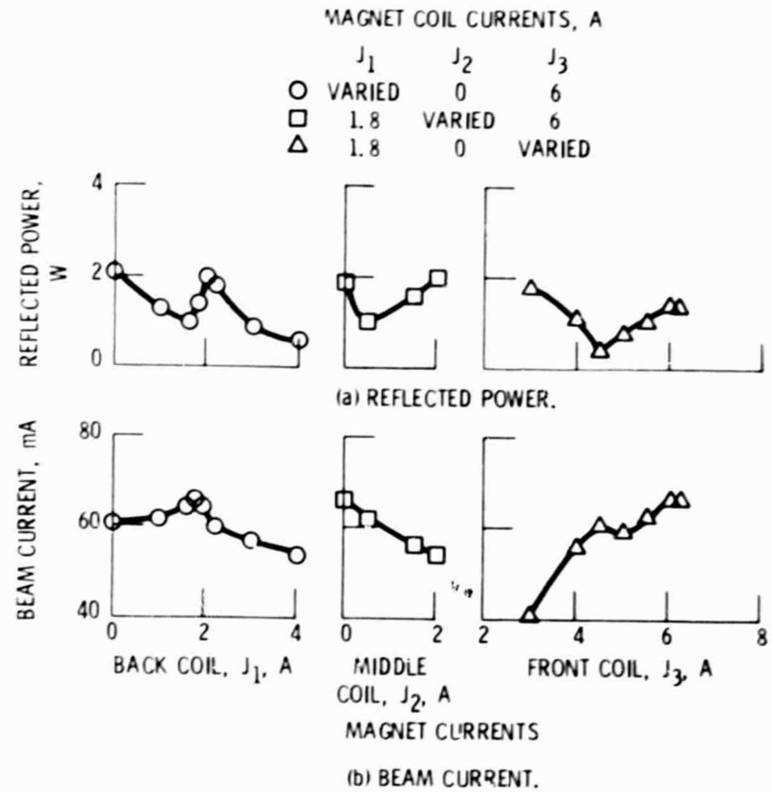

Figure 5. - Effects of magnet coil currents (configuration 2)(incident power, 40 W; frequency, 154 MHz.

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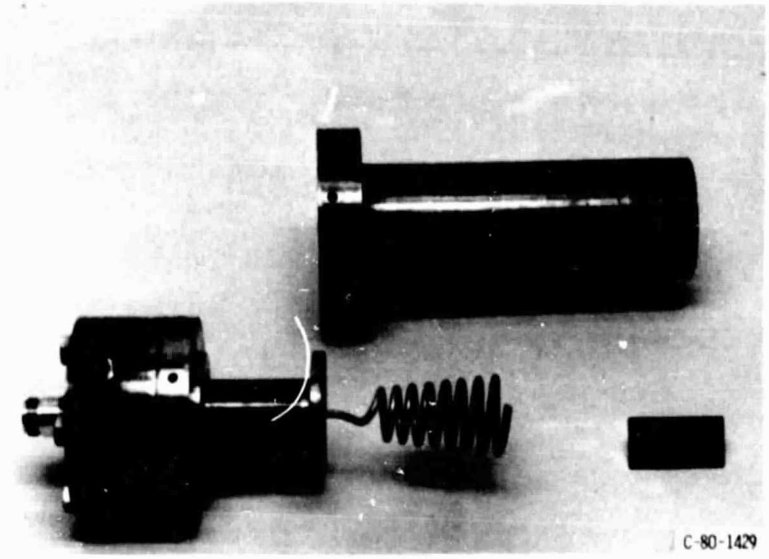
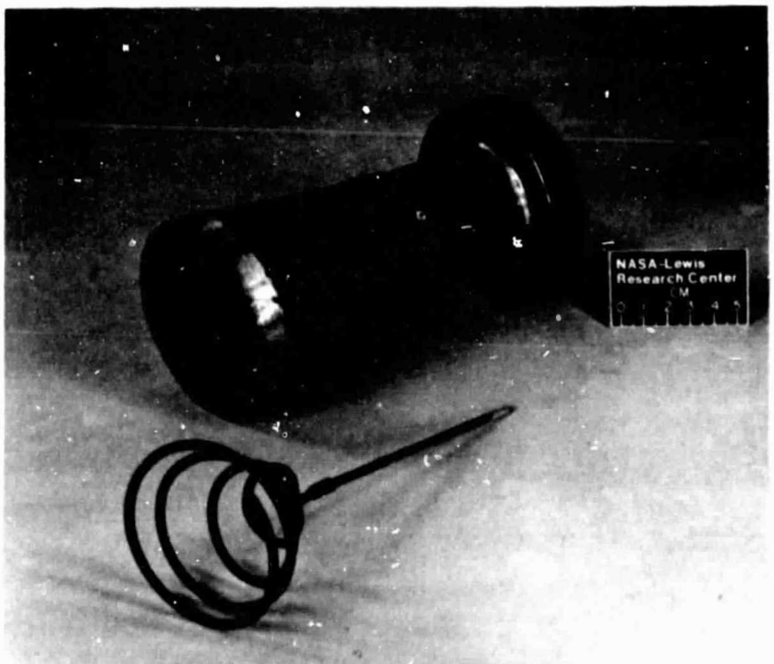


(a) CONFIGURATION 1.



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(b) CONFIGURATION 2.

Figure 1. - Discharge housing and coil coupler.

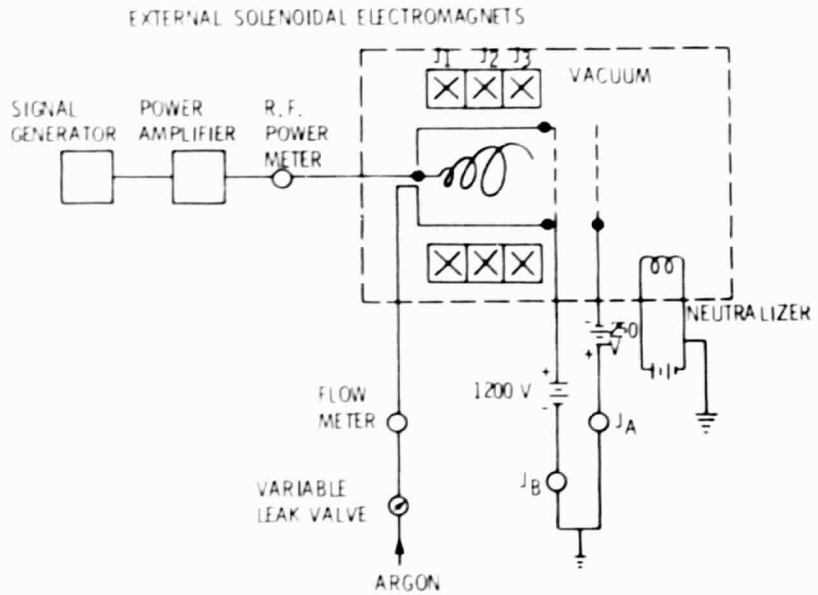

Figure 2. - A schematic diagram of experimental setup.

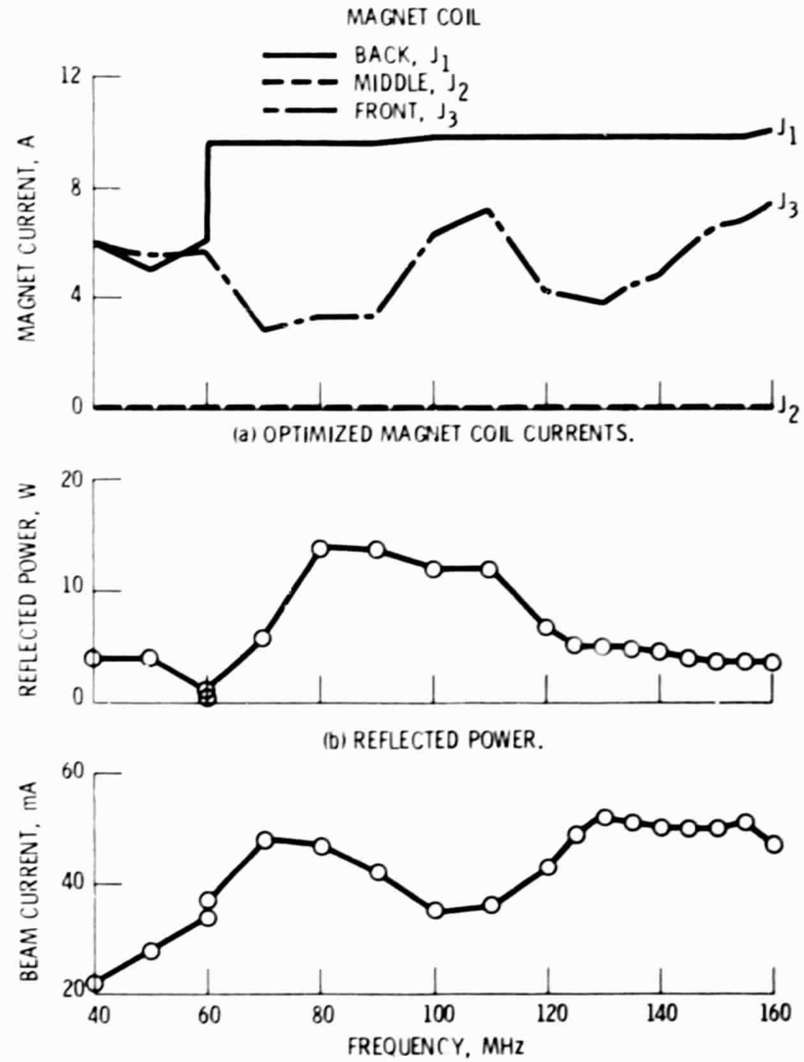

Figure 3. - Characteristics of a constant diameter discharge chamber (configuration 1), incident power, 40 W; argon flow rate, 290 MA Ar^+.