Experiments with an Electron Cyclotron Resonance Plasma Accelerator

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A plasma acceleration system is described in which power is transferred from an rf electromagnetic field to a flowing plasma by means of electron cyclotron resonance coupling An efficient coupling of energy from the rf field to the plasma can be expected if a right-hand, circularly-polarized wave is used and if the flow conditions of the injected gas are properly established The Lorentz force due to the radial component of the fringing magnetic field then converts the electron paths from transverse to longitudinal, and the resulting charge-separation field causes the ions to follow Experimental results obtained with a medium power (320 w), S-band (2 45 kMc/sec) microwave accelerator are presented Plane rather than circularly-polarized waves are used in this system In spite of this, the coupling of energy from the rf field into the plasma can be made to be quite good; efficiencies on the order of 80–90% have been measured The rf-plasma interaction zone is rather narrow in this experiment, thereby not making efficient use of the injected gas As much as 22% of the incident rf power appears in the accelerated plasma stream, however The effects of magnetic field strength, gas density and gas injector location on exhaust stream characteristics, rf-plasma interaction zone thickness, and rf reflection coefficient are described Design considerations resulting from these experiments are discussed

I Introduction

THE fact was recognized[1] and substantiated[2] some time ago that electrical acceleration of charged particles would probably be required to achieve the specific impulses necessary for practical interplanetary travel. Upon this premise, the development of electrical propulsion has proceeded with increasing rapidity over the past few years, and three specific avenues of endeavor—electrothermal, electrostatic, and electromagnetic—have become clearly defined [3]

The electrothermal (arcjet) and electrostatic (ion) thrustors, calling on previously established technologies, have now progressed to the point where they are being considered for early flight testing [4] In contrast, because of the simultaneous complexity and youth of the relevant fields of plasma physics and magnetohydrodynamics, the electromagnetic systems have not been developed to an applicable state as yet However, encouraged by the possibility of operating in a specific impulse range not efficiently covered by either the electrothermal or electrostatic devices,[5 6] several electromagnetic configurations and concepts are currently being investigated

All electromagnetic thrustors are characterized by an electric field from which the charged particles in the plasma propellant gain energy and a magnetic field normal to the electric field which provides a Lorentz force on the currents flowing in the plasma Beyond these two basic characteristics, classification can be made on the basis of frequency (d c , a c , rf) manner in which the fields are applied to the plasma (with electrodes, or inductively, i e , electrodeless), and gross time characteristic (pulsed or continuous wave)

It is the purpose of this paper to describe one of the varieties of electromagnetic systems and to report on some results which have been achieved in the first laboratory tests of this concept The system is referred to as the cyclotron-resonance or continuous-microwave propulsion system The former name indicates one of its unique features, namely that the electric vector of the electric-magnetic field combination is resonated at the electron cyclotron frequency determined by the strength of the magnetic vector; optimum operation results when the electromagnetic field frequency is in the microwave range Additional characteristics are that it is electrodeless and continuous (c-w) In this system, a radio frequency wave is incident upon a flowing gas within a uniform (or slowly diverging) d c magnetic field In this interaction region, the direction of rf field propagation, the stream-flow direction, and the d c magnetic field direction are parallel with one another In addition, the magnetic field strength is adjusted so that electron cyclotron resonance will occur at the rf field frequency [$\omega = (q/m)B$], thereby greatly increasing the rate at which energy is transferred from the rf field to the plasma electrons After the input gas has passed through a certain distance of this interaction region, it has become ionized by the rf field, and its electrons have been accelerated to the desired energy (in transverse cyclotron orbits); then the gas enters the diverging portion of the d c magnetic field where the Lorentz action converts the electron motions from transverse orbits to longitudinal paths out of the accelerator Diffusion parallel with the magnetic field will also aid in moving the electrons out of the rf interaction region [8] The charge separation electric field established by the electrons as they escape serves to accelerate the ions longitudinally along with the electron flow Thus the rf field force is exerted directly on the electrons, while the ions, coupled to the electrons by the charge separation field, represent the majority of the mass flow

This particular propulsion concept was first publicly described in 1962 [7] Measurements on operating thrustors of this and similar kinds have since been reported [8 9] Related (but not necessarily propulsion oriented) theoretical and experimental aspects of electron cyclotron-resonance heating have also been presented elsewhere [10 11]

II Theoretical Aspects

Important operating features of a cyclotron-resonance plasma accelerator have been derived theoretically in Refs

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7–9 and 12 and only will be reviewed here The first important characteristic to note is that all the electrons rotate in the same direction normal to the magnetic field Now, the incident rf wave may be considered to be analyzed into two circularly-polarized components; one whose electric vector, at resonance, rotates with the electron, and the other whose electric vector rotates in the opposite sense With this analysis of the rf field, and ignoring collisional scattering of energies, we can arrive at the significant conclusion that net (time-average) power is transferred to the electrons only from that rf component which rotates with the electrons One then predicts best efficiency when the nonparticipating component of the rf field is eliminated

In order to evaluate the amount of power which is transferred from an electromagnetic field to a plasma, it is convenient to ascribe medium-like properties to the plasma and then to derive a dispersion relation, giving the propagation constant of the electromagnetic field as a function of its frequency within the medium Consider the propagation of a right-hand, circularly polarized wave (i e , that component of the wave which resonates with the electron cyclotron orbits) into a magnetized plasma Also assume that the propagation vector is parallel with the magnetic field For this situation, one can derive the following expression for the propagation constant k from the electron equations of motion:

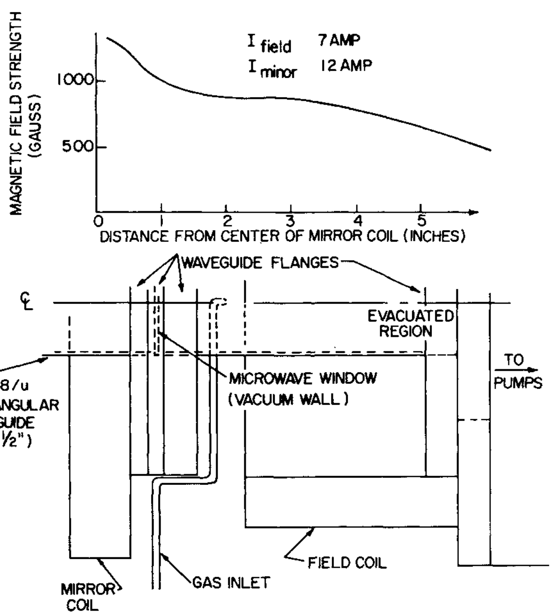

Fig 1 Medium-power microwave plasma accelerator

$$k^2 = \left(\frac{\omega}{c}\right)^2\left[1 - \left(\frac{\omega_{pe}}{\omega}\right)^2\left(\frac{1}{1 - (\omega\ /\omega) + j(\nu/\omega)}\right)\right] \quad (1)$$

where

ω = electromagnetic field frequency, rad/sec
ω_{pe} = plasma electron density frequency, $\omega_p = (q_e{}^2 n_e/m_e\epsilon_0)^{1/2}$
ω_c = electron cyclotron frequency
ν = electron-ion collision frequency

Inasmuch as a wave of the form $\exp j(kz - \omega t)$ has been assumed in this discussion, damping of the wave, representing power transfer from the wave to the plasma, will be indicated by an imaginary component of k This also can be described as a real component of the conductivity σ, since, from Maxwell's equations, one can obtain

$$\sigma = j\omega\epsilon_0[1 - (k^2c^2/\omega^2)] \quad (2)$$

There are two possible mechanisms by which σ can have a real component Collisions, represented by the $j\nu/\omega$ term in the denominator of Eq (1), will of course give rise to wave damping A further and possibly more important source of power absorption arises from Doppler broadening of the resonance due to electrons having a thermal spread in their longitudinal velocities These power absorption mechanisms are discussed more fully in Refs 7 and 12

A further characteristic of interest is the reflection coefficient, relating the amount of power absorbed to the amount of power incident on the plasma (Note that in all cases of interest the plasma will be "deep" enough so that no rf power will be transmitted through the plasma) An approximate guide is given by the plasma electron density frequency ω_p ; if there were no collisions and the plasma electron density rose abruptly to n , then, of course, there would be complete reflection for $\omega < \omega_p$ and complete transmission for $\omega > \omega_p$ If the damping mechanisms just discussed are included, then the resonance is less sharp, with some reflection for $\omega > \omega_p$ and some absorption for $\omega < \omega_p$ A further influential factor is the shape of the electron density profile in the boundary region In particular, a sharp boundary, where the electron density abruptly rises from zero to a maximum value in a very short distance, yields a much higher reflection coefficient than does a gradual boundary [13 14]

In the interests of an efficient system, it is therefore advantageous to optimize the matching of the incident rf wave to the plasma by creating a gradual rf-plasma interface In order that such a tapering electron density profile be realized as a steady-state condition, it is necessary to have a flowing gas situation, in which the electrons are swept downstream as fast as they are created, and new, un-ionized gas is continuously being fed into the rf interaction region If the gas is continuously injected in the downstream direction by some sort of nozzle, then the natural flow of the gas will serve to remove electrons from the interaction region Electron diffusion parallel with the magnetic field will oppose this downstream motion and will instead cause the plasma to "pile up" at the upstream material barrier Additional urging in the downstream direction is therefore generally required, and such action can be achieved by having a gradient in the magnetic field

Consideration of the extraction of the plasma from the magnetic field will not be made here, since it is anticipated that a thorough treatment of this complex problem will be forthcoming in the future as a separate publication The reader is referred to Ref 9 for a simplified analysis of the exit sheath

III Medium-Power Experiments‡

A Expeiimental Apparatus

The experimental studies of the cyclotron resonance propulsion system presented here have been carried out at a medium power (320 w) in the S-band (2 45 kMc/sec) microwave frequency range

At this frequency, the magnetic field required to obtain electron cyclotron resonance is 870 gauss This field is produced by a two coil arrangement which not only provides the required resonance field, but which also provides a magnetic gradient (magnetic mirror) to help prevent back-streaming of the plasma against the microwave/vacuum window (see Fig 1)

The source of microwave power is a QK-390 continuous-wave magnetron This rf power is then coupled through the waveguide circuitry to the thrust chamber where the electromagnetic wave interacts with the flowing gas

Incident and reflected powers are measured by thermistors coupled to the main (generator to thrust chamber) guide in a carefully calibrated reflectometer arrangement This

‡ The results herein presented are extracted from a more extensive set of measurements included in Ref 15

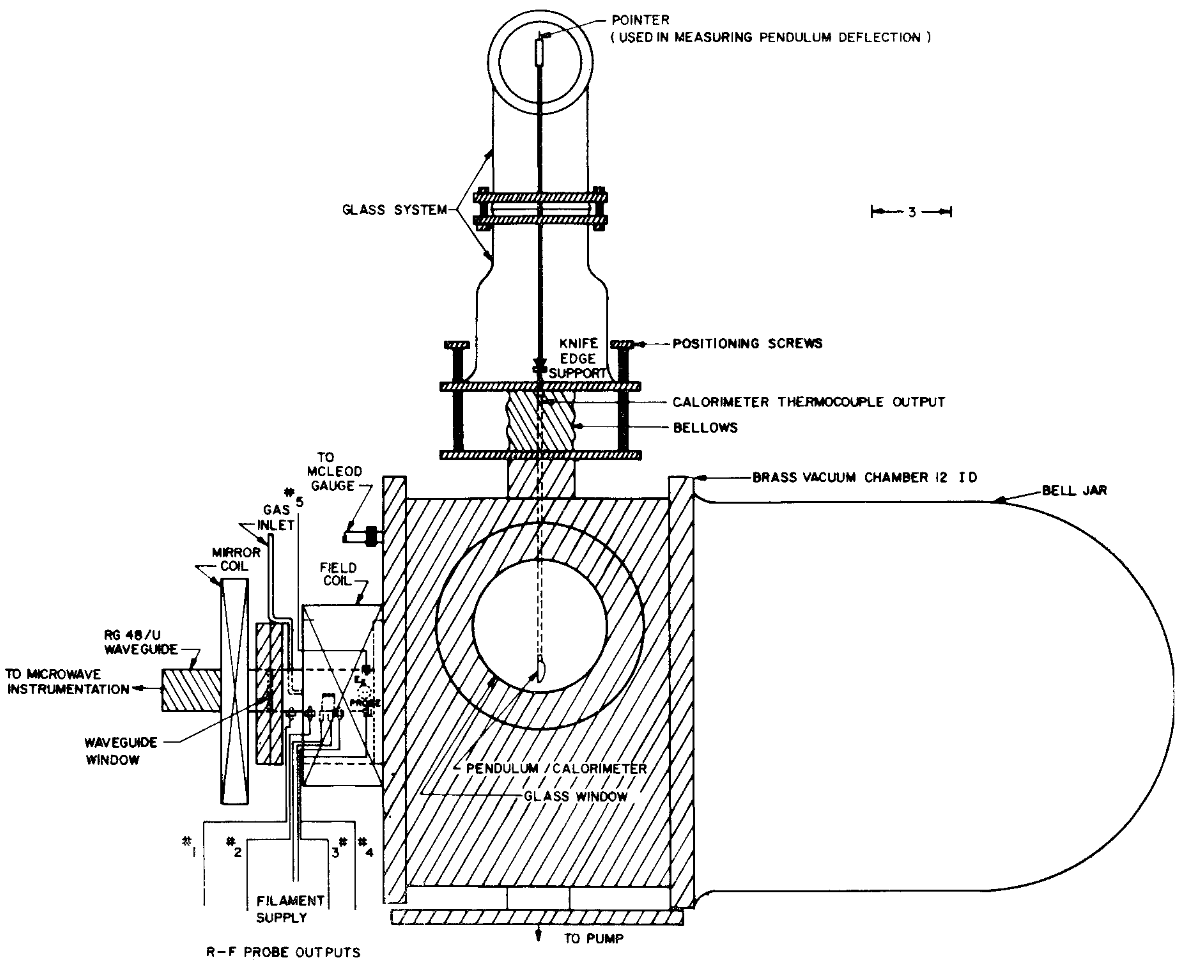

Fig 2 Microwave plasma accelerator (12-cm wavelength) showing instrumentation and vacuum system

measurement enabled us to determine the reflection coefficient and (knowing the rf power generated by the magnetron) to calculate the power transferred to the plasma No matching arrangement was employed in these low-power experiments

The thrust chamber is a section of waveguide which has one end open to the vacuum system and which has its other end sealed by a dielectric vacuum wall through which the microwave energy can pass A $\frac{1}{8}$-in -diam stainless steel tube extending in through the top wall serves as the gas injection nozzle for the thrust chamber (see Fig 1)

A 0 095-in -thick piece of high-purity alumina was used as the back wall of the thrust chamber This piece was subject to considerable heating, perhaps due to electron diffusion parallel to the magnetic field

A thermionic filament was generally required in this experiment to initiate the plasma This filament is a replaceable helix of 0 015-in -diam tungsten wire which is inserted into specially constructed sockets mounted inside the thrust chamber (See Fig 2 for this and following descriptions) Approximately 10 amp, at a few volts, are required to bring this filament up to emission temperature

The rf probes in the thrust chamber are straight wire antennas which protrude a short way into the chamber and which are separated from the plasma by quartz covers The signals from these probes are rectified by crystal diodes and are then displayed on recording millivoltmeters or sensitive oscilloscopes

The pendulum-calorimeter consists of a 12 8 g, 3 1-cm-diam copper cup cemented to a $\frac{1}{8}$-in -diam hollow glass rod and supported by brass knife edges At the top end of the glass rod is a counterbalance which enables the pendulum to be quite heavy and yet sensitive to very small forces Sensitivity is also increased by use of an optical magnifying system to observe deflection A thermocouple, whose electrical connections are brought through the knife edges, measures the temperature of the copper cup The pendulum is calibrated by careful measurement of weight and geometry The calorimeter is calibrated by comparing the thermocouple reading with a calibrated thermometer in a water bath and measuring the change in temperature of a known water volume due to the immersion of the calorimeter at a known initial temperature Note that the radial position of the copper cup is adjustable by means of a bellows system

B Experimental Results

During a run, a visible blue cone of plasma is observed to emerge from the thrust chamber into the 12-in vacuum chamber Each run had a duration of from 35–90 sec during which continuous chart recordings of the calorimeter temperature and of two rf probe voltages and incident and reflected power readings were made These procedures insured steadiness of operating conditions and comparability of data

Figures 3 and 4 show the dependence of reflected power and of probe no 2 signal on axial magnetic field strength and gas density

At the lowest downstream pressure, 3×10^{-5} mm Hg, no plasma is formed and the transmitted power remains essentially constant throughout the range of magnetic field strength It will be noted that the reflected power rises at the higher magnetic field strength This is most likely due to filament current effects as suggested by a rise in emission current at these same points

When the gas flow is increased until the pressure in the test chamber is $1\ 2 \times 10^{-4}$ mm Hg, the particle density is sufficient to maintain an intermittent plasma at the high field strength, as indicated by the "splitting" of the reflected and transmitted power curves Both power readings decrease during plasma conditions and a bright emerging beam is clearly visible in the exhaust region

A further increase in pressure stabilizes the discharge so that plasma conditions are stable and can be repeatably achieved for magnetic fields in excess of the resonance value of 870 gauss Again both the transmitted (probe no 2) and reflected powers decrease below no plasma condition, and relatively high power absorption efficiencies are obtained As the magnetic field is increased, absorption efficiency passes through a maximum at about 1000 gauss, and then begins to decrease at the highest field values Current limitations on our field coil array prevented following this curve further

At the highest pressure setting shown, $1\ 9 \times 10^{-4}$ mm Hg, a second discharge region exists for field strengths of approximately half the value required to initiate lower pressure charges This low field plasma could be maintained for field strengths varying from 400–550 gauss and is characterized by a high reflection coefficient, indicating a highly ionized plasma The high field plasma was also present and again exhibited an efficiency maximum before beginning to decrease at the highest field points

The exhaust stream characteristics were measured by the calorimeter-pendulum In all cases the copper cup was located on a plane $5\frac{1}{2}$ in out from the end of the thrust chamber

Data were taken for two different gas injection conditions In the first case the gas was introduced into the thrust chamber at a point $1\frac{1}{4}$ in downstream from the microwave-vacuum window, and in the second case the injection point was only $\frac{1}{4}$ in from the window

Figures 5 and 6 show the measured plasma stream power density profile for the $1\frac{1}{4}$-in injection point Table 1 tabulates both the energy density and thrust density data for one set of operating conditions It is obvious from these figures that the plasma stream is somewhat "hollow," with maximum energy being carried at some nonzero radius This maximum point appears as a bright cone which is visible within the exhaust stream

Further conclusions which may be drawn from Figs 5 and 6 are that 1) both reflection coefficient and energy efficiency decrease when the magnetic field is increased from 900 gauss (i e , just above resonance) to 1050 gauss, and 2) increasing gas flow rate (and, therefore, raising downstream pressure also) causes the energy efficiency to decrease and the reflection coefficient to become larger

Efficiency characteristics can be deduced from the Table 1 data using the expressions presented in the Appendix Since, however, an explicit measurement of the distribution function $f(v)$ was not obtained, the assumption $\eta_m \equiv 1$ will be made The efficiencies η_p, η_v, and η then follow using Eqs (A7, A8, and A11):

Power Efficiency

$$\eta_p = P_1/P_0 = 0\ 22$$

Velocity Efficiency

$$\eta = T^2/2P_1R_0 = 0\ 046$$

Over-All Efficiency

$$\eta = T^2/2P_0R_0 = 0\ 010$$

Power efficiency§ is at a respectable level considering that these are only initial experiments and no optimization program has been involved It is clear that over-all efficiency is low because of the poor velocity efficiency factor A possible

§ Power efficiency as calculated here compares the plasma exhaust stream power with the incident rf power Thus the power consumed by the thermionic filament and magnetic field coils has been ignored The filament is used to ignite the plasma; turning it off during a run generally has no effect on operating characteristics, and so it is appropriate to neglect this power The field coils were in no way optimized for minimum power; in addition, the field coil power requirement will remain essentially constant as over-all device power increases, and so it is felt that inclusion of coil power in evaluation of this relatively low-power experiment is inappropriate Finally, it should be noted that, while the total plasma stream power is measured, stream spreading is observed to be sufficiently small so that power in transverse motion may be neglected

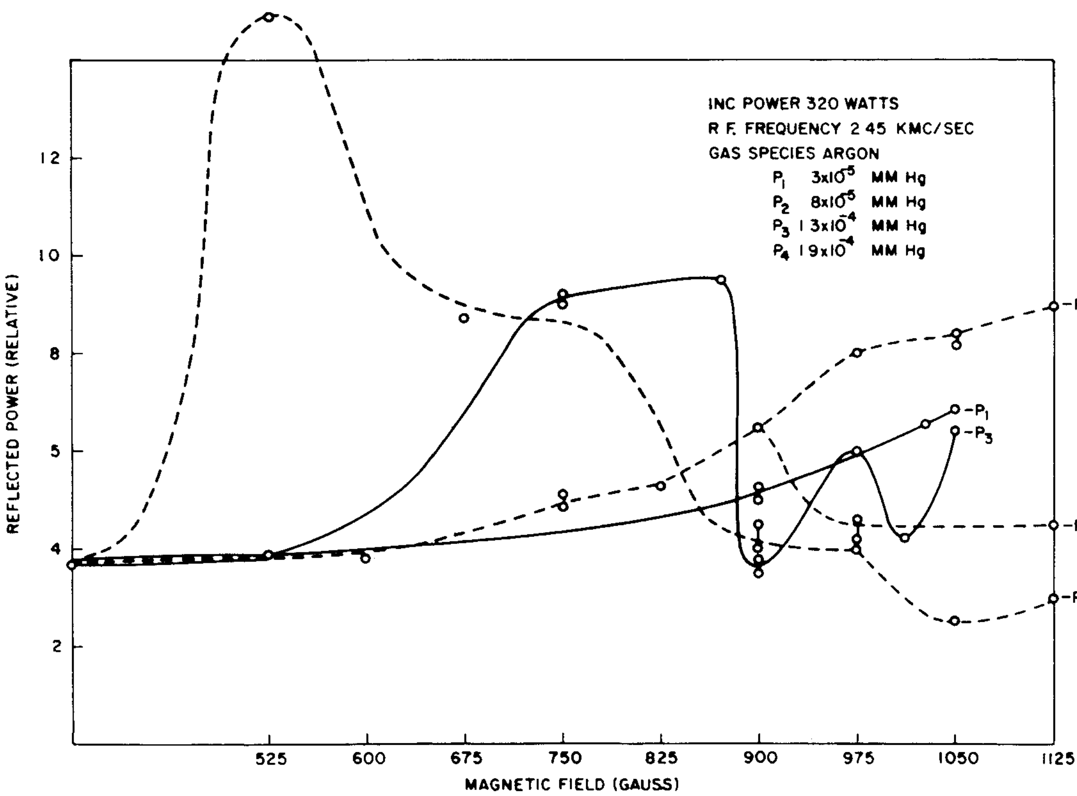

Fig 3 Dependence of reflected power on magnetic field

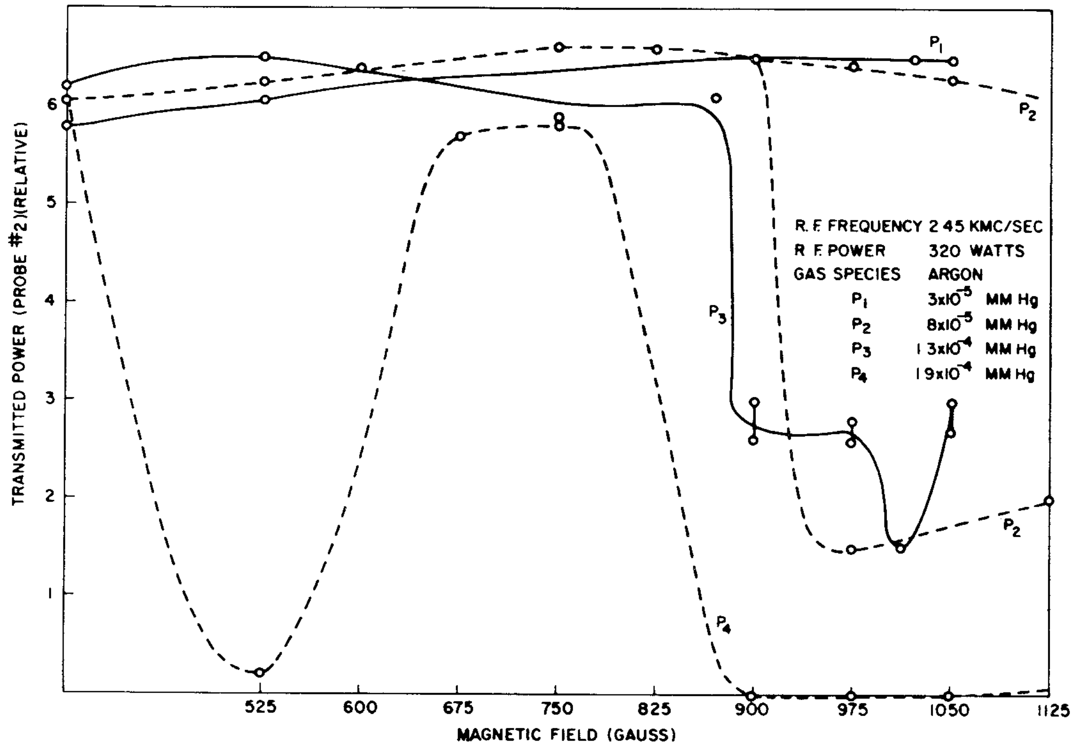

Fig 4 Dependence of rf probe no 2 signal on magnetic field

source of this weakness will be brought out in the following paragraphs

Figure 2 shows the positions of the rf probes no 1 through 5, with no 1 being closest to the waveguide window and to the source of microwave power Table 2 lists the ratio of probe signals with and without plasma under various conditions It is evident from Table 2 that under none of the recorded conditions did any significant rf power get to probe no 2 It is also evident, however, that with the stronger field a large amount of rf power was measured by probe no 1 The fact that the no 1 signal actually increased with plasma in the higher field situation indicates that the major reflecting portion of the plasma existed downstream from probe no 1, i e , between no 1 and 2

It has been theoretically predicted that the reflection coefficient of a plasma will decrease as the plasma boundary becomes more gradual Thus, from the probe measurements of Table 2 and the reflection coefficient values given in Figs 5 and 6, we have evidence that the stronger magnetic field causes the plasma boundary to widen and become more gradual This is possibly due to the "mirror" action of the magnetic field in the region adjacent to the window (see Fig 1) Another important factor, no doubt, is the fact that close to resonance the energy transfer rate is greatest causing the rf field to attenuate more rapidly with distance into the plasma One interesting point that can be made is that little rf power is actually getting to probe no 2 and therefore into the gas flow emerging from the injection nozzle for this $1\frac{1}{4}$-in injection point It appears possible, therefore, that a high-energy plasma stream is generated from the low-density "backwash" gas behind the nozzle, and that, since the mean free path is long, this high-velocity ion stream passes undisturbed through the slowly moving neutral gas The result of this action would be to yield a distribution function with peaks at a very low (thermal) velocity and a very high velocity The mean and mean square velocities for such a distribution would be widely divergent, and, consequently, the velocity efficiency would be very low

In light of the probe measurements, which indicated that very little rf power was actually getting up to the gas injection point, tests were made with the nozzle moved back to a position $\frac{1}{4}$ in downstream from the microwave window The results of these measurements are typified by the data presented in Fig 7 and Table 3

It is observed that moving the injection nozzle reduced the hollowness and spreading of the plasma stream In addition, thrust density and power density both increased, but the increase was not sufficient to offset the decrease in plasma stream cross-sectional area; both total thrust and total exhaust stream power decreased

Efficiency factors, as defined in the Appendix, may be derived from the Table 3 data: $\eta_p = 0\ 048$, $\eta = 0\ 038$, and $\eta = 0\ 002$ Comparison of these values with the equivalent ones for the initial nozzle location shows that characteristics have generally deteriorated Variations of gas flow rate and magnetic field resulted in power efficiencies as high as 10%, but the $1\frac{1}{4}$-in nozzle location values were never exceeded Thus, we can conclude that, while the plasma cross-sectional profile was improved by moving the gas injection point, other characteristics were made worse This result points out the important influence which the thrust chamber geometry has on operating characteristics of this type of accelerator

IV Conclusions

The important results of the experiments reported here are that an electron cyclotron resonance plasma accelerator has actually been operated on a continuous basis and that its thrust-producing ability has been demonstrated In addition, power conversion efficiency was found to be quite good, although other operating parameters were not as favorable These studies suggest that a method of coupling the rf power more directly into the main stream of the injected propellant (by suitable alteration of the thrustor geometry) may be the key to improvement of the velocity efficiency factor Of course, gas species and magnetic field shape will also be influential factors deserving further study

Appendix: Plasma Engine Efficiency Factors

Let a velocity distribution function $f(v)$ be defined by

$$f(v)dv = dR_1 \qquad \text{(A1)}$$

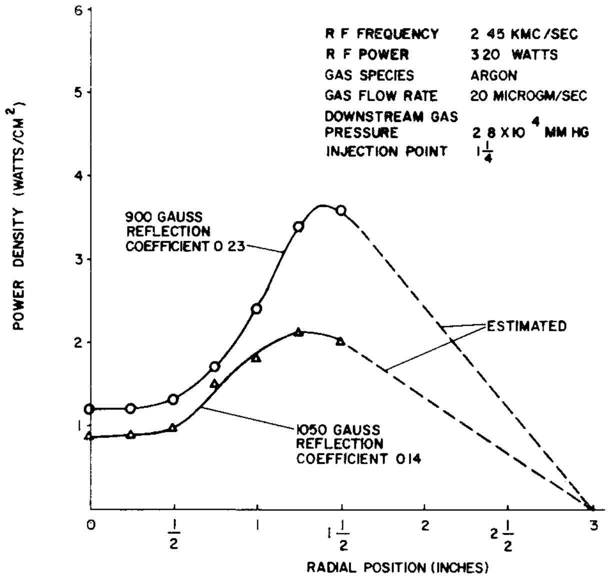

Fig 5 Microwave accelerator plasma stream power density profile

where dR_1 is the mass flow rate (kg/sec) of propellant particles whose longitudinal velocities at the engine exit plane lie in the velocity increment v, dv The total propellant mass flow leaving the engine is then

$$R_1 = \int_v f dv \tag{A2}$$

where integration is carried over the total range of longitudinal velocities

Mean and mean square velocities are expressed in terms of f as follows:

$$\bar{v} = \frac{1}{R_1} \int_v v f dv \tag{A3}$$

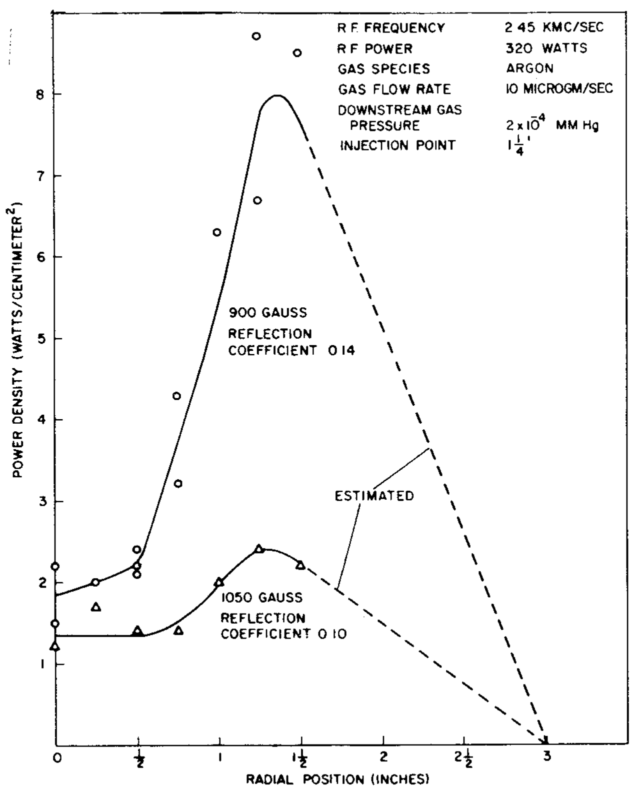

Fig 6 Microwave accelerator plasma stream power density profile

Table 1 Microwave accelerator plasma stream characteristics[a–c]

Radial position, in	Power density, w/m²	Thrust density, newtons/m²
0	1 8 × 10³	0 021
1/4	2 0	0 024
1/2	2 2	0 027
3/4	3 7	0 024
1	5 4	0 023
1 1/4	7 7	0 024
1 1/2	7 7	0 024
2 1/2 (estimate)	2 5	0 010

[a] Rf frequency 2 45 kMc/sec; rf power (incident) 320 w; rf reflection coefficient 0 14; magnetic field strength 900 gauss; gas inlet flow rate 0 01 × 10^{-3} g/sec; downstream gas pressure 2 × 10^{-4} mm Hg; gas species argon; gas injection point 1¼ in
[b] Total exhaust stream power (P_1) ≅ 70 w
[c] Total exhaust stream thrust (T) ≅ 2 6 × 10^{-4} newtons

$$\overline{v^2} = \frac{1}{R_1} \int_v v^2 f dv \tag{A4}$$

Integration of the momentum equation applied to an accelerating space vehicle system results in the following expressions for thrust (T) and power (P_1) in longitudinal motion of the exhaust stream:

$$T = R_1 \bar{v} \tag{A5}$$

$$P_1 = \tfrac{1}{2} R_1 \overline{v^2} \tag{A6}$$

The over-all efficiency (η) of an electric propulsion engine can be expressed in terms of three efficiency factors:

Mass Efficiency

$$\eta_m = R_1/R_0 \tag{A7}$$

where R_0 is the mass flow rate of propellant fed into the engine; η_m may be greater than unity if wall material is eroded and enters the propellant stream

Power Efficiency

$$\eta_p = P_1/P_0 \tag{A8}$$

where P_0 is the power input to the engine

Velocity Efficiency¶

$$\eta = (\bar{v})^2/\overline{v^2} \tag{A9}$$

Over-all efficiency is then given by

$$\eta = \eta_m \eta_p \eta \tag{A10}$$

$$= T^2/2P_0R_0 \tag{A11}$$

Table 2 Microwave plasma acceleration rf probe characteristics[a]

Gas inlet flow rate, μg/sec	Downstream pressure, mm Hg	Magnetic field, gauss	Ratio: plasma/no plasma rf no 1	rf no 2	rf no 3
~10	2 × 10^{-4}	900	0 014	0 016	0 01
		1050	1 1	0 014	0 005
~20	3 × 10^{-4}	900	0 023	0 021	0
		1050	2 3	0 021	0
~40	4 × 10^{-4}	900	0 29	0 013	0
		1050	5 7	0 025	

[a] Rf frequency 2 45 kMc/sec; rf power 320 w

¶ Note that this is identical with Hunter's "beam power efficiency"[16]

Table 3 Microwave accelerator plasma stıeam chaı acteristics[a–c]

Radial position, in	Power density, w/m²	Thrust density, newtons/m²
0	$5\ 6 \times 10^{3}$	$5\ 0 \times 10^{-2}$
$\frac{1}{4}$	5 9	3 6
$\frac{1}{2}$	5 8	5 9
$\frac{3}{4}$	5 6	4 1
1	3 7	3 6
$1\frac{1}{4}$	2 2	3 3

[a] Rf frequency 2 45 kMc/sec; rf power (incident) 320 w; rf reflection coefficient, 0 5; magnetic field strength 1030 gauss; gas inlet flow rate $0\ 02 \times 10^{-3}$ g/sec; downstream gas pressure $2\ 7 \times 10^{-4}$ mm Hg; gas species, argon; gas injection point $\frac{1}{4}$ in

[b] Total exhaust stream power $(P_1) \cong 15$ w
Total exhaust stream thrust $(T) \cong 1\ 6 \times 10^{-4}$ newtons

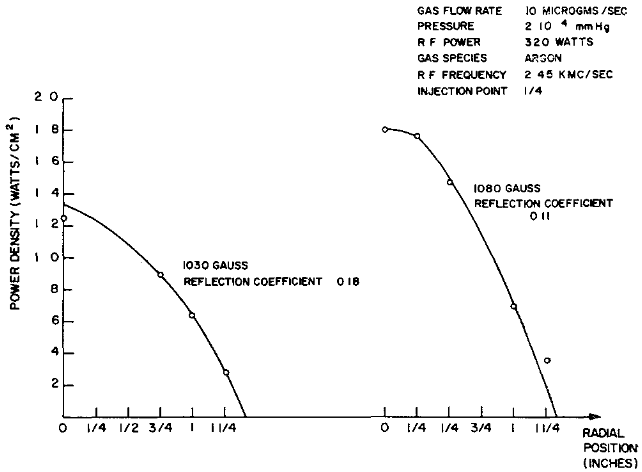

Fig 7 Microwave accelerator plasma stıeam power density profile

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