# Radial Field Kaufman Thruster

W. Knauer,* R. L. Poeschel,† and J. W. Ward†
*Hughes Research Laboratory, Malibu, Calif.*

**A thruster is described in which radial and axial elements of the Penning-type discharge have been exchanged. With the predominantly axial magnetic field replaced by a predominantly radial field, electrons can move freely across the ion extraction screen. The resulting radially uniform plasma distribution provides two advantages: 1) ions are generated at a low cost of energy and 2) few propellant atoms escape as neutrals. Tests were performed with a 15 cm hollow cathode mercury thruster. Without major optimization a low power consumption of 190 ev/ion at 90% propellant utilization could be achieved. Furthermore, the ion beam profile was found to be unusually flat. Consequently, in low specific impulse applications, where the perveance limit restricts beam current density, the radial field thruster can deliver considerably more thrust than conventional thrusters.**

## Introduction

In Kaufman thrusters the low-pressure gas is ionized by a Penning discharge-type configuration in which the electrons remain trapped. In early thrusters, confinement was provided by a uniform magnetic field which extended axially through the cylindrical discharge chamber. Since the cathode was located on the axis, primary electrons were confined to the central region of the discharge; this led to a plasma distribution which was highly peaked in the center. Peaked density and electron temperature distributions are undesirable for two reasons. 1) Propellant atoms can escape relatively easily along the outer regions of the discharge where plasma density and electron temperature are low. Accordingly, high propellant utilization can be achieved only through an excessively high central plasma density, which results in excessive discharge power losses. 2) The ion beam profile is peaked in the center and thus the perveance of the ion-optical system is utilized unevenly. Ultimately, this imposes an unfavorably low limit upon the thrust level.

The magnetic field configuration of the SERT II thruster has improved the situation considerably.[1] Diverging magnetic field lines help to spread the primary electrons more evenly across the diameter of the discharge. This results in lower discharge losses and a less peaked ion beam. However, electrons still must diffuse radially outward to reach the anode and thus still require radial density gradients.

We describe herein a configuration in which a radial gradient is not required. This is accomplished through an exchange of the radial and axial elements of the Penning discharge configuration (see Fig. 1). The predominantly axial magnetic field is replaced by a predominantly radial field. A flat disk in the rear of the chamber is used as the anode. The outer chamber cylinder, which formerly served as the anode, is now maintained at cathode potential. A post, mounted along the discharge axis, is used as a second electrode at cathode potential. The center post and part of the outer cylinder are of soft iron and serve as pole pieces for the radial magnetic field. In addition, a hollow cathode is located inside the center post and a series of holes provide the passageways necessary for electron injection into the discharge.

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* Head, Propulsion and Space Physics Section. Member AIAA.
† Member of the Technical Staff. Member AIAA.

## Thruster Performance

A 15-cm-diam experimental discharge chamber was used to test this concept (see Fig. 2). Magnetic flux was provided by solenoids and the propellant was injected in the reverse direction. The propellant flow was determined from the decrease of the mercury level in a calibrated standpipe where constant flow was maintained for at least 4 hr. Furthermore, two ion accelerator systems with 74.7% and 71% transmission were used interchangeably (NASA Lewis Research Center grid sets No. IV and VI, Ref. 1). Remarkably good performance was attained after only a minor tune-up effort. Figure 3 shows the discharge energy expenditure as a function of propellant utilization for two ion beam current levels and for the two accelerator systems. Discharge parameters of interest for one of the better operating points (185 ev/ion — 91% propellant utilization) are given in Table 1. It should be noted that the hollow cathode and feedline heater powers shown in this table were obtained with an experimental arrangement in which no regard was given to power economy. With a more adequate thermal design the hollow cathode heater power could readily be kept below 15 w (equal to the SERT II hollow cathode power). Similarly, the feedline power should not exceed 5 w. This would increase the electrical efficiency from 87% to 91% and the total efficiency from 78% to 81%.

The discharge voltage of the radial field thruster was found to depend upon the size and number of holes in the center post. A relatively high voltage range between 40 and 45 v was selected for high performance. This choice was based upon results of a recent basic investigation of hollow cathode thruster discharges.[2] It was found that the plasma ad-

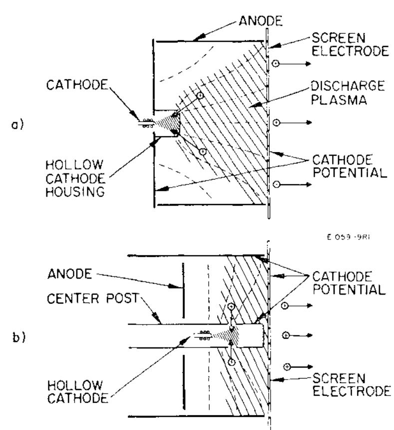


**Fig. 1 Thruster discharge configurations; also shown are the ion trajectories in the hollow cathode region. a) Conventional thruster. b) Radial field thruster.**

**Table 1 Radial field thruster parameters for a selected operating point**

Discharge, 43 v, 1.12 amp
Propellant flow, (total) 293 ma equiv.
Beam, 3000 v, 0.265 amp
Decelerating, 2000 v
Drain current, 0.0034 amp

| Power, w | | Efficiency, % | |
|---|---|---|---|
| Beam | 795 | Electrical | 87 |
| Drain | 6.8 | Propellant | 90 |
| Discharge | 48.2 | Thruster | 78 |
| Cathode | 33 | Perveance Utilization | 67 |
| Keeper | 2.4 | | |
| Isolator | 4.2 | | |
| Vaporizer | 3.6 | | |
| Feedline | 25 | | |

jacent to the hollow cathode adopts a low-level potential $v_h$ of about 12 v above the cathode. The electrons of this plasma are well thermalized and possess an average energy $ev_{th}$ on the order of 1 ev. Eventually, they are drawn into the discharge plasma which resides near anode potential $v_d$. The power which the injected electrons deliver to the discharge plasma and which can be employed usefully to generate ions amounts to $I(v_d - v_h + v_{th})$, where $I$ is the discharge current. The total power input into the discharge chamber is $Iv_d$. Thus, the hollow cathode plasma consumes a portion $I(v_h - v_{th})$ which is unproductive loss and should be minimized. A step in this direction is to increase the discharge voltage. This permits a lower discharge current and thus reduces the power losses in the hollow cathode plasma.

A potential problem with operation at high discharge voltages is sputter damage to the hollow cathode tip. In order to prevent such damage, the voltage of conventional hollow cathode thrusters is kept below about 36 v[3]. Based on a comparison of the presumed ion trajectories in both situations, we believe the radial field thruster can be operated safely at higher voltages. According to Fig. 1, discharge ions of conventional thrusters are accelerated toward the cathode tip by the potential gradients between the discharge and hollow cathode plasmas. In the radial field thruster, acceleration takes place perpendicular to the tip. Accordingly, fewer ions reach the cathode tip in the latter case. This conclusion appears to be supported by observations. At the end of a 24-hr performance test (see Table 2 for 4-hr average data) the hollow cathode face appeared to be sputtered only very mildly. Furthermore, erosion was more evenly distributed across the cathode tip than in conventional configurations.

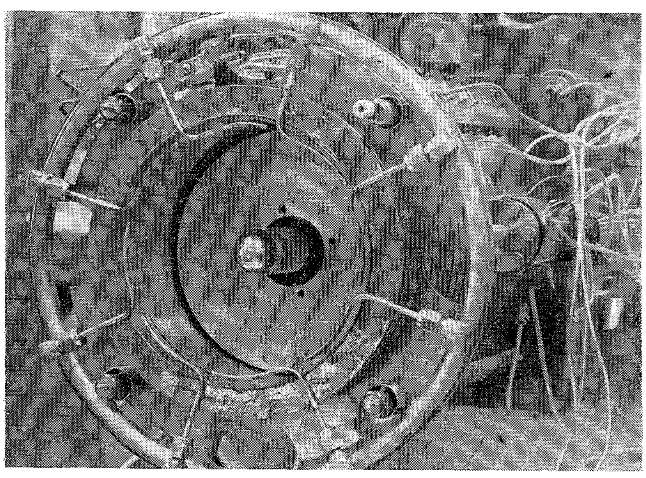

**Fig. 2 Experimental 15-cm radial field thruster configuration; ion accelerator removed.**

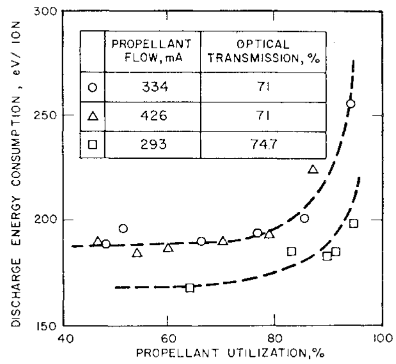


**Fig. 3 Discharge energy expenditure of the radial field thruster.**

In addition to possessing a lower energy consumption rate than any known mercury Kaufman thruster, the radial field thruster provides a very uniformly distributed ion beam. Figure 4 shows the beam profile obtained using a Faraday cup probe about 1 cm downstream from the ion acceleration system. The striking beam flatness is perhaps the most significant asset of the radial field thruster. In order to appreciate the importance of a flat profile, one must consider that with low specific impulse thrusters the small dimension of the ion optical system sets a practical limit to the perveance, or current carrying capability. In the case of a peaked plasma distribution, this limit is reached only in the center and the rest of the ion optical system is not fully utilized. Quantitatively, the utilization of an ion optical system by a thruster may be expressed as

$$\epsilon = 2\pi \int_0^{r_b} jrdr/\pi r_b^2 j_{\max}$$

where $j$ is the current density at radius $r$, $j_{\max}$ is the current density maximum, and $r_b$ is the ion beam radius at the screen electrode. We label $\epsilon$ perveance utilization and express it in percent. Analysis of measured beam profiles has shown that the perveance utilization of SERT II-type thrusters amounts to about 40% while that of the radial field thruster reaches 67%. Therefore, with identical ion accelerator systems, the same beam voltages, and the same projected life expectancy of the accelerator electrode, the radial field thruster should deliver about 1.7 times more thrust than a conventional thruster.

The performance data given in Fig. 3 substantiate this contention. The radial field thruster performs as well at a propellant flow level of 426 ma as at 334 ma. Furthermore, at an ion beam current of 400 ma the perveance limit of the ion acceleration system is not nearly reached, as may be concluded from the small accel electrode current which remains below 4 ma.

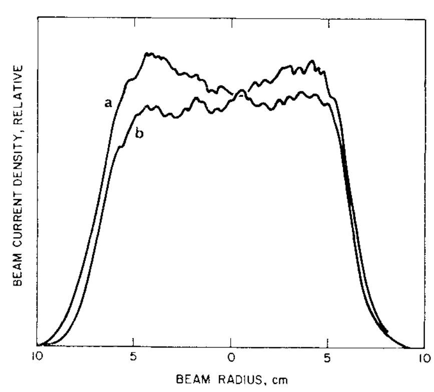


**Fig. 4 Ion beam profiles of the radial field thruster at 1 cm distance from accelerator electrode. Total beam current = 400 ma. a) Low propellant flow through hollow cathode. b) High propellant flow.**

Table 2 Four-hour averages of radial field thruster parameters monitored during 24-hr test

| Hours | $v_D$, v | $I_D$, amp | $I_B$, ma | $I_A$, ma | $I_N$ (total), ma (equiv.) | $I_N$ (Hollow Cathode), ma (equiv.) | $\eta m$, % | $\epsilon I$, ev/Ion |
|---|---|---|---|---|---|---|---|---|
| 1–4 | 46.2 | 1.05 | 274 | 1.6 | 344 | 36.2 | 80.2 | 177 |
| 5–8 | 47.2 | 1.13 | 259 | 1.6 | 316 | 41.6 | 82 | 205 |
| 9–12 | 45.7 | 1.12 | 269 | 1.4 | 304 | 39.6 | 88.6 | 190 |
| 13–16 | 47.1 | 1.02 | 252 | 1.5 | 336 | 35.6 | 75.1 | 192 |
| 17–20 | 46.7 | 1.09 | 252 | 1.4 | 294 | 30.2 | 85.6 | 201 |
| 21–24 | 47.0 | 1.07 | 250 | 1.6 | 315 | 32 | 69.4 | 195 |
| 24 hr average | 46.6 | 1.08 | 260 | 1.5 | 318 | 35.8 | 81.6 | 193 |

## Thruster Diagnostics

In order to understand why the radial field thruster performs so well, a number of diagnostic measurements were performed. These comprised iron filing tracings of the magnetic field; Langmuir probe measurements of plasma density, plasma potential, and electron temperature; and Faraday cup measurements of the ion beam profile.

Figure 5 shows magnetic field tracings of the radial field thruster in the configuration which led to the performance characteristics of Fig. 3. The values of the radial magnetic field strength obtained with a movable gauss probe are also shown. It can be seen that electrodes and magnetic fields together provide the desired Penning discharge-type confinement. Electrons injected from the hollow cathode into the discharge are well trapped. They must diffuse under a predominantly axial density gradient toward the anode. On their way they have sufficient time to ionize the propellant.

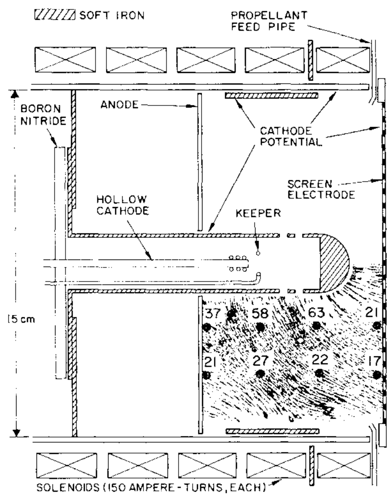


**Fig. 5 Magnetic field configuration of the radial field thruster. Numbers represent radial magnetic field strength in gauss.**

Results of Langmuir probe measurements are shown in Fig. 6. The observed plasma density and electron temperature distributions are quite unusual. In conventional thrusters, both plasma density and electron temperature decrease with radius throughout the discharge chamber.[2] In the present case, they decrease with radius in the rear. However, near the ion extraction system both increase with radius. It is not unreasonable, therefore, that the ion beam should have a flat profile.

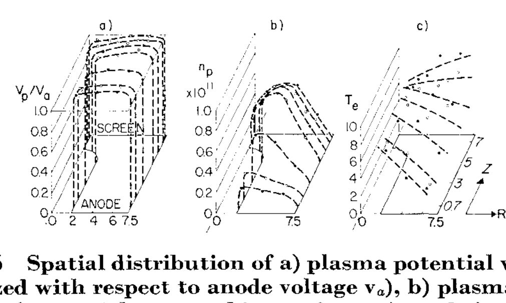


**Fig. 6 Spatial distribution of a) plasma potential $v_p$ (normalized with respect to anode voltage $v_a$), b) plasma density $n_p$ (in particles per cubic centimeter), and c) electron temperature $T_e$ (in electron volts). Distances $z$ and $R$ (in centimeters) point in the direction of the discharge axis and discharge radius, respectively.**

To explain the radial plasma density increase one must consider that electrons which orbit in a magnetic field are required to conserve angular momentum. Therefore, as the electrons move radially inward to regions of higher magnetic field strength, kinetic energy parallel to the magnetic field must be converted into transverse kinetic energy. Electrons which start inward with a small amount of parallel kinetic energy are reflected as soon as they have exhausted that energy. In other words, the radial magnetic field serves as an outward directed mirror for many electrons.

Figure 6a shows the measured plasma potential distribution. The potentials slope axially as well as radially. An axial gradient in the direction of the ion acceleration system is very desirable because it accelerates ions toward the location of ion extraction. The radial gradient is unfavorable because it leads to the interception of ions by the center post; intercepted ions lose their charge and must be reionized at a cost of extra energy.

## Conclusions

We can summarize our investigations by stating that the radial field thruster fully satisfies the two most important requirements for efficient thruster operation. First, by providing a Penning discharge-type configuration it confines the electrons sufficiently to make efficient use of the kinetic electron energy for ion production. Second, by providing a radially uniform plasma density it confines the propellant atoms effectively, so that the propellant utilization can be high while the discharge power expenditures remain low. The radial plasma uniformity has the additional and important advantage of providing a flat ion beam profile.

We can anticipate still further improvements for the radial field thruster in the future. The ultimate configuration should provide not only satisfactory propellant atom and electron trapping but also better confinement for the ions. This implies that ions should not be able to reach any portion of the discharge chamber walls, including the center post. It might be possible to prevent ions from reaching the center post by using the type of periodic magnet confinement which we have tested recently in a separate thruster configuration called "Cusped Field Thruster."[2] A similar configuration has been explored by R. D. Moore.[4] Another area of improvment is that of ion extraction. The fact that the performance of the radial field thruster improved by about 10% as the transmission of the ion acceleration system was increased from 71% to 74.7% suggests that further gains are still possible.

## References

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# Laboratory Testing of the Space-Charge-Sheath Electric Thruster Concept

R. X. Meyer*
*The Aerospace Corporation, El Segundo, Calif.*

**Recent experimental results obtained with a laboratory model of the space-charge-sheath thruster are reported. The principal feature of this thruster is the electrostatic acceleration of ions in a space-charge sheath that is formed on the ionizer. The range of operating conditions tested was as follows: specific impulse = 2700–5500 sec; magnetic field strength = 800–2500 gauss; accelerating gap = 1–3 mm; ionizer surface = 13.8 cm$^2$; cesium vapor pressure = 5–38 mm Hg; ion-beam current density = 4–14 ma/cm$^2$. The resulting ion-beam has been found to be surprisingly well collimated, with an estimated half angle of 1.5°. Under best operating conditions, the electron drain current to the anode (ionizer) was 31% of the total current.**

## Introduction

EXPERIMENTAL results obtained with a laboratory model designed to test the space-charge-sheath electric thruster concept are reported. The operating mode of this device and some initial experimental results have been described previously.[1,2]

Cesium ions, which are produced by contact ionization on a hot tungsten surface, are accelerated electrostatically in the space-charge sheath formed between the ionizer and the beam plasma (Fig. 1). No accelerating electrodes are employed; instead, a heated tungsten filament is used for electron emission and a transverse magnetic field serves to suppress the electron current to the ionizer. The emitting filament can be located at a relatively large distance from the beam, thereby avoiding erosion through ion sputtering. The ionizer is at a positive potential, and the emitting filament (cathode) is grounded.

The device is operated in a regime in which the electron cyclotron radius is only slightly smaller than the gap between the ionizer and the magnetic field lines intersecting the filament. The ion cyclotron radius is so large, however, that the ions leave the strong magnetic field region before the trajectories are appreciably bent.[1]

As indicated schematically in Fig. 2, the ionizer has an annular configuration. A radial magnetic field is maintained between two concentric pole pieces. The cricular emitting filament is located near the outer periphery of the ionizer annulus.

Since, except for infrequent collisions, the electrons are free to move along the magnetic field lines, the latter are also approximate lines of constant electrostatic potential and form a virtual cathode in close proximity to and parallel to the ionizer surface. Since the spacing between virtual cathode and ionizer can be quite small (of the order of 1–3 mm), a high perveance per thruster module is possible.

The device has some similarity to Hall current plasma thrusters.[3–7] However, in Hall current thrusters, the acceleration of the ions takes place in the interior of an electrically neutral plasma instead of in a space-charge sheath, and extends over a distance which is much larger than an electron cyclotron radius. By confining the acceleration to the space-charge sheath region, the present device attempts to avoid the plasma wall losses, which seem to be inherent in Hall current and other magnetohydrodynamic thrusters. The present device is space-charge limited, however, a property that it shares with contact and electron bombardment type ion engines.

Potential advantages of the space-charge-sheath electric thruster concept include the absence of an ion-optical structure and therefore avoidance of ion sputtering and the resulting deterioration of the accelerator electrode. The high degree of beam collimation that was observed in the experiments may be of importance in certain applications when impingement of the ion beam on other spacecraft components must be avoided.

## Electron and Ion Trajectories

Under the combined influence of the axial electric and the radial magnetic fields, the electrons and ions experience an azimuthal drift. In Fig. 3 are shown computed electron trajectories corresponding to two different magnetic field strengths. These trajectories, which are qualitatively similar

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* Director, Plasma Research Laboratory.

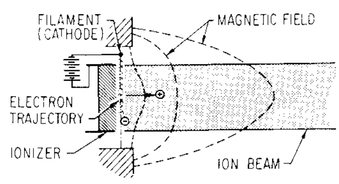


**Fig. 1 Schematic diagram of space-charge-sheath electric thruster. The figure represents a radial cross section through the thruster.**