CHANNEL ION SOURCE

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Abstract

A channel ion source has been developed and performance tested for application to plasma processing and electric space propulsion. Major design features of the channel ion source included a distributed permanent magnet circuit, an axially located and embedded hollow cathode, and a double plenum anode/gas manifold assembly. A laboratory model 10 cm total diameter channel ion source of mass 2.0 kg was evolved from a design iterative test program. This source was operated stably from 25 W to 900 W of input power. Reliable, single power supply operation of the channel ion source was demonstrated. Both argon and xenon gases were used successfully in the channel ion source, with the latter gas having a much greater propellant utilization efficiency and higher ion current for a given discharge voltage. Hollow cathode gas flow rates were typically 5% of the total channel ion source gas flow. Average beam ion energy for argon was 30%-60% of the discharge voltage, and 50%-70% of the discharge voltage for xenon. Ion beam divergence was measured from beam ion current density profiles at about 18° full width half maximum. Channel insulator ion sputter erosion was noted and erosion sites determined.

Introduction

A high energy ion source using electrodeless ion acceleration has been developed for space propulsion applications in the former Soviet Union. A review and reference source for these Hall current, or Stationary Plasma Thrusters (SPT's), is provided by Brophy. A Hall current thruster, or SPT, has also been reported in work by Komurasaki. The basic ion acceleration mechanism for the SPT is well known, as described by Cann. Similarly, significant variants of the SPT concept are presented by Valentin. A thruster with anode layer, TAL, has also been developed as an alternative to the SPT. The type of device uses an acceleration process predominately external to the thruster body in an attempt to eliminate the channel insulator erosion behavior of the SPT. Published data does not support any meaningful performance advantage with the TAL type of thruster geometry, and does show significant metallic sputter erosion processes around the downstream thruster face.

The SPT and TAL devices are particularly useful when relatively high thrust, in the 1,300-1,600 s specific impulse range, is desired for efficient spacecraft orbit control. Flight applications of SPT's are many, and further flight programs of both SPT and TAL devices are in process.

Existing SPT and TAL devices utilize electromagnets whose solenoids are energized either by the discharge current, or by a separate power supply. A separate power supply adds system complexity. Using the discharge current to energize the electromagnet solenoids limits the low power throttling capability of these devices, and significantly reduces performance at low throttled powers. Also, existing SPT and TAL devices use externally mounted hollow cathodes which adds to the volume packaging envelopes of the thrusters.

This paper describes a channel ion source developed to address both of these design and operational issues.

Key Features

A total of forty five different channel ion source configurations were tested during this program. Part of this effort was to understand the key design issues of this type of device, and also to create a channel ion source which could be manufactured at relatively low cost by using simply machined components and readily obtainable materials.

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Source Design

Figure 1a shows a cross-sectional view of the channel ion source. Sources were fabricated and operated with outside diameters ranging from 7 cm to 13 cm. However, the 10 cm total outside diameter channel ion source design shown in Fig. 1b was selected as a good compromise for source operation up to input powers of order 1 kW. This maximum input power level is adequate for orbit control of smaller spacecraft, and for most plasma processing applications. In Fig. 1a the channel magnetic field is established by identical Alnico V rod permanent magnets, magnetized along their long axis, positioned circumferentially around the source body as shown. The magnets may be either rods, bars, sectors, or even one single thin ring. A hollow cathode is embedded within the center of the circular source. The hollow cathode, magnetic circuit components, and anode/manifold structure, are attached to a thin alumina mounting disc which provides both mechanical support and electrical isolation. Gas is injected into the source at the base of the hollow cathode, and in the main gas inlet tube which is connected to the dual plenum anode/manifold assembly. The dual plenum feature, and appropriate orifice sizing and shaping, ensure uniform anode/manifold pressurization from a single inlet gas line, with subsequent uniform gas flow injection into the ionization and acceleration annular channel of the source. A more complete description of the channel ion source design may be found in Ref. 10.

Fig. 1a Sectional view of typical channel ion source. 1: Rod permanent magnet, 2: channel, 3: channel insulator, 4: hollow cathode, 5: anode/manifold, 6: pole pieces, 7: gas inlet, 8: back plate, 9: support rod.

Fig. 1b 10 cm total diameter channel ion source tested in this program on argon and xenon up to 900 W.

Operating Principle

The plasma processes occurring to ionize, accelerate, and space-charge neutralize the ion beam from the channel ion source are depicted schematically in Fig. 2. Neutral gas atoms are indicated by the letter “o”, electrons by the sign “-”, and ions by the sign “+”. Operation of the source is initiated by starting the hollow cathode discharge between the emitter and the enclosed keeper electrode. For the channel ion source, gas flow through the hollow cathode is usually about 5% of the total source gas flow. To start the source, a potential of a few hundred volts positive of the cathode emitter is applied to the anode/manifold. This voltage difference attracts hollow cathode discharge electrons into the channel toward the anode/manifold where they are confined by the strong radial magnetic fields to short radius Larmor orbits. Gas atoms admitted into the channel from the anode/manifold undergo inelastic collisions with these accelerated electrons and are ionized. Subsequent electron collisions enable the electrons to work their way through the radial magnetic flux lines where they eventually join the surface of the
anode/manifold to complete the current path of the source discharge power supply.

![Diagram of Anode/Manifold Hollow Cathode Schematic](image)

**Fig. 2 Schematic representation of the plasma processes occurring to ionize, accelerate, and space-charge neutralize the ion beam of the channel ion source.**

Confinement of the electrons to the strong magnetic flux lines in the channel ion source, as shown in Fig. 2, means that the confined electrons act as virtual negative accelerator electrodes. Ions created in this region are accelerated by these virtual electrodes in a predominately axial direction out of the channel. The channel magnetic flux lines closest to the anode/manifold have a positive potential near that of the anode/manifold. The magnetic flux lines beyond the exit of the channel have a potential near that of the hollow cathode. It is important to note that this acceleration mechanism is essentially electrostatic in nature. Moreover, since ion acceleration is through a quasi-neutral plasma, via virtual electrodes defined by electrons confined to magnetic flux lines, there is no space-charge limit to the accelerated ion current density, as is the case in an ion source using discrete electrodes, or grids.

Movement of the electrons to the anode/manifold results in a generally azimuthal motion of these electrons around the channel as a result of the interaction of this electron current with the predominately radial magnetic field. This general azimuthal motion of electrons around the channel is referred to as a Hall current and is responsible for the ability of this type of accelerator to typically function with an external edge mounted hollow cathode, with little channel discharge plasma non-uniformity. Similarly, the ions formed in the channel are also acted on by the radial magnetic field as they are accelerated towards the exit. However, because the ions are so much more massive than the electrons, the azimuthal velocity they receive is relatively low. Nevertheless, the small azimuthal, or Hall, velocity component imparted to the ions results in a small torque on the channel ion source. This torque has been measured in other similar devices and found to have only a minor effect on thrusting functions for space applications.

Embedding the hollow cathode on the axis of the channel ion source maximizes the symmetry and efficiency of the electron coupling between the anode/manifold and the hollow cathode. In turn, this maximizes the efficiency with which electrons are drawn from the hollow cathode for a given unit of gas flow. Moreover, embedding the hollow cathode axially removes it from potential beam ion sputter erosion. Similarly, for ground based plasma processing applications, argon or xenon may be passed through the hollow cathode while reactive gases such as oxygen, fluorine, chlorine, etc. may be passed through the anode/manifold without communication of these reactive gas ions with the hollow cathode.

**Magnetic Field Distribution**

The magnetic field strength in the channel ion source is very high. Figure 3a shows the calculated magnetic flux distribution and Fig. 3b shows the measured radial magnetic field strength with increasing distance downstream from the anode/manifold face. The two field plots shown in Fig. 3b represent measurements taken at two different orthogonal locations in the channel. The similarity in measurements highlights the uniformity and high field strength in the channel. Reducing the strength of this radial field by reducing the number of rod permanent magnets reduces the magnitude of the discharge voltage, $V_D$, that can be supported in the channel, and this reduces the energy of the beam ions. However, reducing the radial magnetic field strength allows a greater electron current to pass from the hollow cathode to the anode/manifold, and thus permits more beam ions to be produced. Hence, for a given ion source discharge power, a higher channel radial magnetic
field strength means a lower discharge current, $I_D$, and lower beam current, $j_B$, while a lower channel radial field strength means a higher beam current, $j_B$, but lowers the energy of the ion beam.

The channel ion acceleration process also depends on the axial variation of the radial magnetic field strength. Reducing the gradient of the axial magnetic field between the anode/manifold and channel pole pieces, by further separating these components, increases the axial extent of the ionization region, and causes a greater ion loss to the insulated channel surfaces.

In general, it has been observed that azimuthal variations of the maximum magnetic field in the critical channel pole piece region should not exceed about 5%. Figure 3c plots a typical variation of the radial magnetic field intensity for the 10 cm channel ion source.

Fig. 3a Numerical calculation of flux distribution of the channel ion source permanent magnet circuit.

Fig. 3b Measured radial magnetic field strength from anode/manifold at two orthogonal locations in the channel of the 10 cm source.

Fig. 3c Measured radial magnetic field strength from anode/manifold at two orthogonal locations in the channel of the 10 cm source.

measured at the maximum field location, for different azimuthal positions around the channel. Use of Alnico V magnets allows source operation to be extended to high input power loadings, since this type of magnet material may be used up to 450-500 °C without significant demagnetization effects.

Performance

All operation of the channel ion source was in a 0.6 m dia. x 1.9 m long diffusion pumped vacuum test facility. Background pressures during source operation were typically of order mid 10⁻⁸ Torr. These pressures were low enough to result in a relatively small source gas back-flow from the test facility. This small gas back-flow claim was further supported by the annular channel exit area of only 25 cm² in the 10 cm diameter channel ion source shown in Fig. 1b. Tests conducted with the channel ion source were concerned with gaining a general understanding of the operational characteristics and performance potential of the device.

Both argon and xenon gas were used to operate the channel ion source. Most of the development effort was concerned with argon since this relatively
inexpensive gas is most commonly used in ground based plasma processing applications. Due to this bias, the geometry of the channel and magnetic field of the 10 cm diameter source shown in Fig. 1a reflected optimization for use of the much lighter weight argon gas. By way of example, the relatively long axial channel length, and narrow width, seen in Fig. 1a denotes the need to contain this gas for as long as possible to make up for the inherently lower gas utilization efficiency of argon as compared to xenon. Consequently, the results obtained with the 10 cm channel ion source using xenon are conservative since the source was not optimized for this gas.

Current, Voltage and Mass Flow Characteristics

Figure 4a shows the effect on the total gas flow requirement as the channel ion source discharge current was increased at a constant discharge voltage of 300 V. Operation of the source annular channel plasma discharge was in a current regulated mode, which meant that the discharge voltage was controlled by flow rate changes for a given discharge current set point. Source operation was stable and the anode/manifold gas flow rate could be readily adjusted to obtain source operation to within one volt of the desired discharge voltage operating point. In general, source operation was not very sensitive to the percentage of gas flow through the hollow cathode. Most source operating tests were performed at hollow cathode gas flow rates about 5% of the total source gas flow.

The channel ion source could be operated reliably at very low input powers, as is evidenced by the data in Fig. 4b which shows stable source operation during power throttling from 600 W to 25 W, for a constant xenon gas flow of 1.72 mg/s. Maximum investigated input power to the 10 cm source at a discharge voltage of 300 V was 900 W as noted in Fig. 4a. However, rod magnet temperature measurements indicated that input powers of order 1 kW could be readily attained at 300 V without damage to the magnetic circuit. Discharge voltages were investigated up to 450 V. Higher discharge voltage operation was not desirable for the prototype devices fabricated in this study since the relatively simple segmented channel insulator assemblies were not designed to support such high stand-off potentials.

At discharge currents above about 2 A, the channel ion source hollow cathode could be operated in a
At fixed xenon flow, the 10 cm channel ion source could be throttled down from 900 W to an input power of only 25 W.

self-heating mode where power to the cathode was reduced to zero. Depending upon the type of hollow cathode used, it is possible to pre-heat the cathode with the discharge supply, start the cathode with the discharge supply, and operate the channel ion source entirely on the single discharge supply.

Ion Current Density and Beam Divergence

The Russian Hall type thrusters and the channel ion source presented here are designed to operate at high ion beam current densities, and fairly low beam ion energies. Such operation ensures relatively high thrust at the moderate specific impulse levels most desirable for earth orbit spacecraft application. However, when operated in a vacuum test facility, the high gas flow rates used in these devices, and their less than unity gas utilization efficiency, mean that significant charge exchange conversion of the beam ions to neutral atoms occurs in the exhaust plume. Consequently, Faraday probe measurements of the beam ion current density from these devices must account for these effects. Figure 5 plots measured Faraday probe beam ion current density measurements, corrected for charge exchange ion production, during xenon operation of the 10 cm channel ion source at various input power levels from 600 W to 900 W. These data were obtained with the Faraday probing system 22 cm downstream from the source exit plane. Beam ion current densities measured with argon were less than for xenon, at the same source input power levels, and this effect was attributed to the inherently lower gas utilization efficiency of argon.

At a constant discharge voltage, the channel ion source beam divergence was not significantly affected by changes in discharge current, or the type of operating gas. Figure 6 plots the measured ion beam divergence characteristics of the channel ion source during operation on argon at a discharge voltage of 300 V, and a discharge current of 2 A. The total beam divergence angles in Fig. 6 correspond to the cones enclosing the percentages of beam ions noted in this figure. Thus, one could expect to contain 95% of the beam ions from the channel ion source in a cone of enclosed angle 53°. For comparison purposes, the full width half maximum (FWHM) beam divergence definition as used by others, when applied to the channel ion source beam ion current density profiles shown in Fig. 5, yields a FWHM beam divergence of about 18°. This measurement is comparable to the Russian thrusters.
Fig. 6 Beam divergence typical of argon operation at a discharge of 300 V and 2 A. Total beam capture cone divergence angles are shown. Corresponding full width half maximum (FWHM) beam divergence was about 18°.

Beam Ion Energy

The energy distribution of beam ions leaving the channel ion source was measured using a retarding potential analyzer. Figure 7 plots the calculated beam ion energy distribution inferred from these plume probe measurements during source operation on argon at a discharge voltage of 300 V, and a discharge current of 2 A. In general, the average beam ion energy for argon was found to be about 50-60% of the discharge voltage, while the average beam ion energy for xenon was found to be about 60-70% of the discharge voltage. Ion sputter rate measurements of silicon samples positioned downstream of the source exit plane supported these average beam ion measurements.

Erosion

For ease of manufacture and cost reduction, the various insulator channel sections and cover plates depicted in Fig. 1a were fabricated from alumina. Erosion of this alumina was noted on the interior channel surfaces towards the channel exit. This erosion was not quantified, but its rate was estimated qualitatively by drawing pencil lead lines at different locations on the interior channel sections, and observing the erosion pattern of these lines as the source was operated. These tests revealed that the outside perimeter of the interior channel surface eroded faster than the inside perimeter of the channel surface. This difference appeared to be about a factor of 2-3. No other erosion was noted on the channel ion source during operation. Although the 10 cm channel ion source was only tested for a period of tens of hours, the channel erosion did not appear significantly different from that found typical of Russian SPT devices. However, for ground based applications, where parts per million surface contaminants can ruin certain processes, and where deposited alumina can significantly retard concurrent sputter etching processes, the channel erosion was unacceptably high. Other materials more resistant to sputtering from accelerated channel ions than alumina are required for ground based application of the channel ion source. Ideally, these materials should have a high resistance to sputter ion erosion in a preferred direction, and a high thermal conductivity in a preferred direction. Such materials could include boron nitride, both hot pressed and pyrolytic, and various composites thereof.
Summary

The 10 cm channel ion source appears to be a viable candidate for space propulsion applications at input powers of order 1 kW or less. Plasma processing applications of the channel ion source are much more sensitive to channel insulator erosion processes and more work is required in this area. Although no thrust stand measurements were taken with the source, discharge plasma operating data, beam current density, and beam energy measurements suggest gas ionization, ion acceleration, and propellant utilization efficiencies are comparable to existing Russian thrusters. Moreover, the channel ion source has a small compact packaging volume, and throttles well over a very wide input power range.

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