

A Proposal to Develop a Two-Stage Gridless Ion Thruster with Closed Electron Drift

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Abstract

The development of a two-stage gridless ion thruster with closed electron drift is proposed. By combining the ionization stage of an ion engine with the acceleration stage of a Hall thruster the favorable characteristics of both systems are realized. This allows variable specific impulse operation spanning the range 1000-4300 s at 35-75% efficiency. Phase one development will design and analyze a working ionization chamber. Phase two modifies the PEPL-70 Hall thruster for two-stage operation by adding an ionization stage. Phase three builds a thruster and optimizes its performance. The research begins September 1999 and concludes August 2002.

Objectives

The purpose of this proposed research is the design and fabrication of a two-stage Gridless Ion thruster with Closed electron drift (GIC). The GIC improves existing concepts for two-stage Hall thrusters by decreasing the ion production cost (eV/ion) of the ionization stage by allowing independent operation from the acceleration stage. These gains are realized by replacing the usual first stage with what will closely resemble the ionization chamber of a traditional ion engine (e.g. NSTAR). Thus, GIC may be thought of as a cross between an ion engine and a Hall thruster. An important advantage of GIC is that it is a gridless device, which will remove a primary failure mode of ion engines.

Performance goals of the thruster include variable specific impulse operation ranging from low to high power operation. At low power (<2kW), dual-mode operation is envisioned, with optimization of the thruster at 1200 and 1800 s specific impulse with corresponding overall efficiencies of >40% and >50%. These operating parameters will make the thruster a primary candidate for commercial and military satellites. At medium power (2-4 kW), operation comparable to the NSTAR thruster will be obtainable, corresponding to 3300 s specific impulse, >66% efficiency, 2.3 kW power, and >8,000 hrs lifetime. Primary application of such a thruster will be on New Millennium class missions. At high power (4 kW – MW), operation at >4000 s specific impulse at >75% efficiency will also be possible, at current densities fifty times greater than NSTAR type thrusters. For a 1 MW thruster this represents the difference between a 7 m diameter ion engine and a 1 m diameter Hall thruster. Such a thruster will find application on piloted interplanetary missions such as a round-trip mission to Mars.

Theory

In single-stage Hall thrusters, shown schematically in Figure 1, ions are accelerated by the electric field established between a downstream cathode and an upstream anode¹. An applied radial magnetic field in an annular discharge chamber impedes the motion of migrating electrons due to the crossed electric and magnetic fields creating an azimuthal closed electron drift, the Hall current. Propellant is injected at the anode and collisions in the closed drift region create ions. The ionization and acceleration processes in such a configuration are closely linked, limiting the useful operating range of the thruster to around 2500 s specific impulse and <60% efficiency². Operation below these values results in intolerable decay in thruster efficiencies (<35% efficiency around 1200 s specific impulse)².

Ionization and acceleration can be made more independent by the introduction of an intermediate electrode in the channel, a two-stage Hall thruster. Figure 2 is a schematic of a traditional two-stage Hall thruster³. The intermediate electrode acts as the cathode for the ionization stage and the anode for the acceleration stage. This allows the ionization stage to operate at high currents and low voltages resulting in higher propellant utilization and the acceleration stage to operate at variable voltages resulting in a wide specific impulse range of operation. Overall thruster efficiency is enhanced in this configuration, as Equation 1 illustrates⁴.

$$\eta_t = \frac{1}{1 + I_d V_d / I_a V_a} \quad \text{Equation 1}$$

where η_t is the overall efficiency, I is current and V is voltage, and the subscripts 'a' and 'd' refer to the acceleration and discharge (ionization) stages, respectively. Thus, efficiency is increased for low discharge voltages and high acceleration voltages. Work by Tverdokhlebov⁴ on a two-stage anode layer thruster demonstrated high efficiency

(>67%) at high acceleration voltages (>500V), but was unable to lower the discharge voltage below 50 V because backstreaming electrons were not of sufficient energy to maintain the discharge. Therefore, in such a configuration the ionization and acceleration processes are still weakly coupled due to the dependence of the discharge on backstreaming electrons. Further, operation of such a thruster has not yet been shown to be efficient at power <6 kW and <2500 s specific impulse³⁻⁵. It is clear that a configuration that does not depend on backstreaming electrons is warranted so that discharge voltages may be minimized and ion production costs lowered.

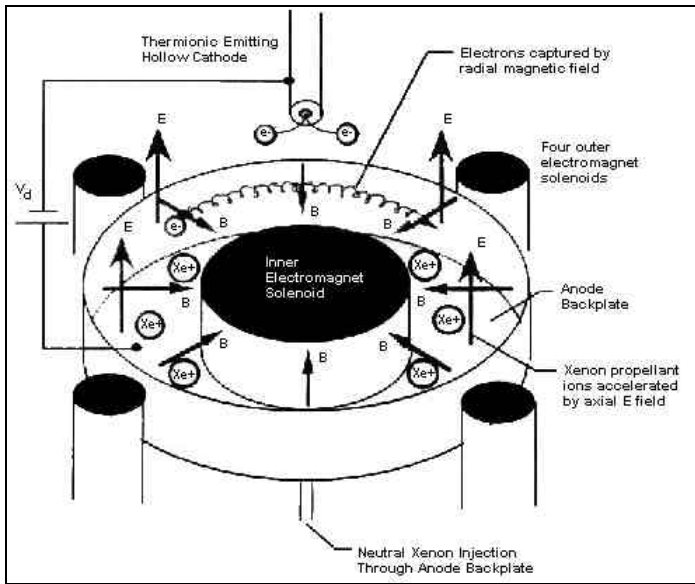


Figure 1 - The basic Hall thruster components showing the potential drop between the cathode and anode, magnetic field circuitry, and the closed electron drift induced by the crossed electric and magnetic fields. (Diagram borrowed from Reference 1)

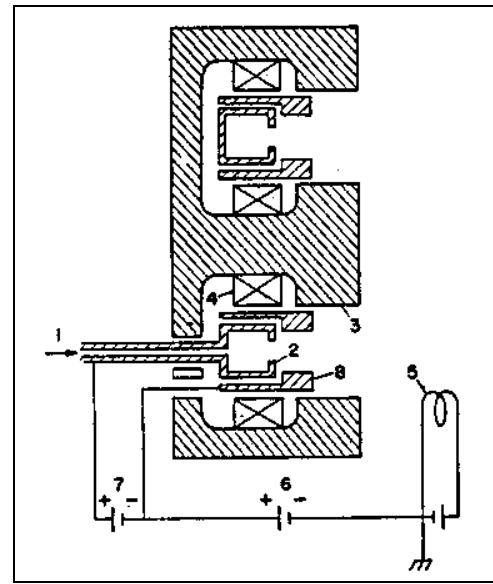
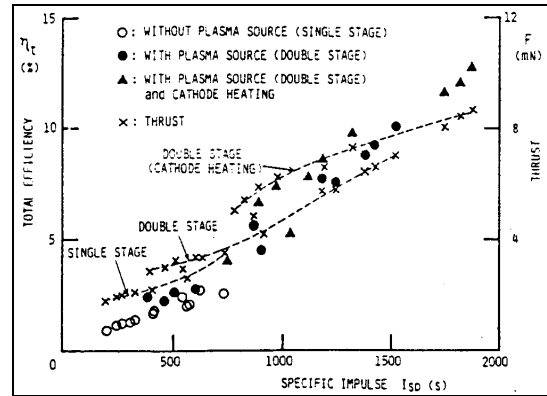
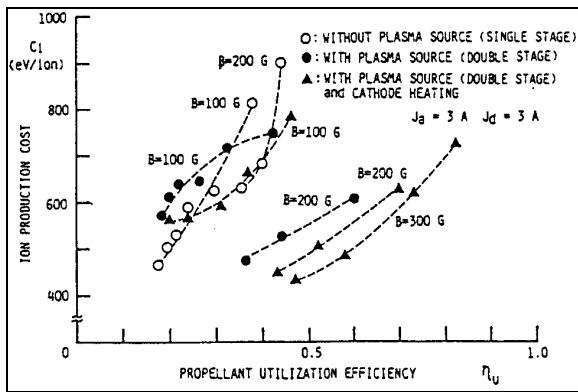


Figure 2 - Typical two-stage Hall thruster (with anode layer). 1) Propellant feed, 2) anode, 3) magnetic circuit, 4) magnet winding, 5) cathode neutralizer, 6) acceleration stage potential, 7) ionization stage potential, 8) intermediate electrode. (Diagram borrowed from Reference 3)

Researchers in Japan have shown that using an emitting intermediate electrode will significantly increase the efficiency of the device⁶. These results are shown in Figures 3a and 3b. The two-stage device with cathode heating outperforms single- and double-stage (no cathode heating) operation. Note that the efficiency of this device is very low, but this is believed to be caused by poor design owing to a long channel length and not to any physical constraints. The trends demonstrated in Figure 3 clearly indicate that an emitting intermediate electrode will increase overall efficiency. In addition, neither the Japanese work referenced here or any previous work known to the author have used magnetic fields expressly designed for the purpose of enhancing ionization, a technique commonly used in ion engines with great success.

The GIC will combine both effects, an emitting intermediate electrode and tailored magnetic fields, to increase the ionization efficiency. This research will therefore develop what may be considered a hybrid ion engine and Hall thruster. Figure 4 is the proposed configuration. A hollow cathode will act as the intermediate electrode providing the electrons to maintain the discharge in the ionization chamber. The thruster body is maintained at the cathode keeper voltage. The usual upstream cathode maintains the Hall current in the acceleration region. A separate magnet system in the ionization stage is used to enhance ionization efficiency since the requirements for optimum performance of the two stages differ. Thus, the acceleration and ionization stages will be essentially independent processes having been isolated both electrically and magnetically. Discharge will no longer depend on backstreaming electrons from the acceleration stage and operation at <50 V will be possible. This will allow the thruster to be throttled over a wide operating range for the particular mission at hand. Since operation of both single- and double-stage Hall thrusters have been shown to span 1000-4300 s specific impulse at 35-75% efficiency²⁻⁶, similar performance can be expected for the GIC.



Figures 3a and 3b – Data from Reference 6, a Japanese Hall thruster using an emitting intermediate electrode (cathode heating). 3a) Ion production cost versus propellant utilization. 3b) Total efficiency or thrust versus specific impulse. The double stage thruster with cathode heating has the best performance in both figures. The extremely low efficiency is not believed to be indicative of two-stage Hall thrusters, but rather of poor design. This thruster does not use ionization stage magnets and the channel length was excessively long.

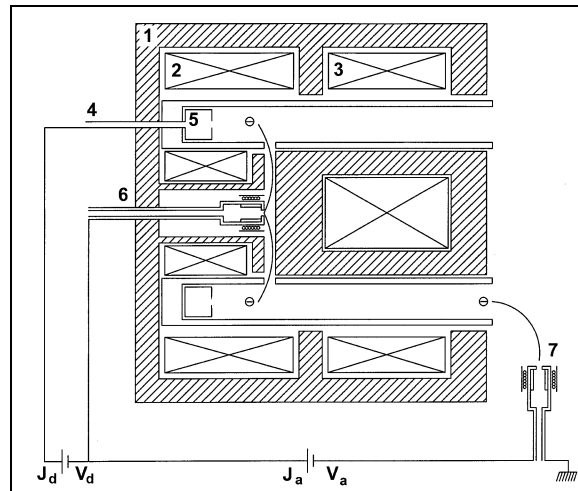


Figure 4 - Proposed configuration of the two-stage Gridless Ion Engine with Closed Electron Drift (GIC). 1) magnet pole pieces, 2) ionization stage electromagnet coils, 3) acceleration stage electromagnet coils, 4) propellant inlet, 5) anode, 6) hollow cathode acting as an intermediate electrode, 7) neutralizer cathode.

Methodology

To achieve the performance goals of this new thruster class, the proposed research will involve three main phases, each phase consisting of computational modeling, construction, and experimentation. In the first phase, an ionization chamber will be constructed demonstrating that low ion production cost can be achieved using a hollow cathode in concert with magnetic fields. The second phase will involve the modification to two-stage operation of an existing laboratory Hall thruster, the PEPL-70. In the third phase, a complete thruster will be built that will demonstrate the concept as a whole. The experience gained at PEPL by the construction of two previous Hall thrusters, the PEPL-70 and the 5 kW PEPL-170², will be drawn on extensively. These devices have performed impressively and demonstrated this lab's capability to build these types of thrusters.

Developing an ionization chamber that will operate more efficiently than a traditional two-stage Hall thruster at discharge voltages similar to ion engines (<50V) is the goal of phase one. Computational modeling will begin the design, using a particle acceleration code (Simion) and a magnetic field code (Quickfield). Licenses to both codes are owned by PEPL. The modeling results will be used to design the magnetic field topology and operation of the hollow cathode. An ionization chamber will then be constructed and tested. Data from mapping of the electric field, number

density, and electron temperature using a Langmuir probe and mapping of the magnetic field with a Hall probe will be used to minimize the ion production cost.

The goal of phase two is to mate the ionization chamber from phase one with the acceleration stage of the PEPL-70. The PEPL-70 is a 1.4 kW single-stage Hall thruster owned by PEPL (80 mN, >50% efficiency). The PEPL-70 is shown in Figure 5. Key to this phase is determining the optimum channel length for efficient operation. Phase two will begin with using the results of phase one to improve the computational modeling. Before the PEPL-70 is modified a benchmark performance test will be conducted at PEPL and LeRC over the operating range of the thruster. Plasma properties will be mapped as in phase one with the addition of time-of-flight mass spectroscopy and ion energy analysis using the PEPL Molecular Beam Mass Spectrometer (MBMS). Modeling results will then be used to modify the PEPL-70 to incorporate the ionization chamber from phase one. Spacers will be used to vary the channel length as necessary. The modified PEPL-70 will be benchmarked and the results compared to the unmodified thruster. These studies will be used to predict the optimum sizing for a new thruster, to be built in phase three.



Figure 5 - The 1.4 kW PEPL-70 Hall thruster.

Phase three will use the phase two results to design a complete thruster. Modeling in this stage will consider the thruster as a whole, without the constraint of pre-existing dimensions as in the PEPL-70 phase. As with the PEPL-70, the performance will be benchmarked and modifications to the thruster made to achieve an optimum design. The final goal is to construct a high efficiency (35-75%), variable specific impulse thruster (1000-4000 s) that will be a viable candidate for a wide-array of space missions.

Schedule, Key Elements, and Milestones

As shown on the schedule in Figure 6 the need arises beginning September 1999 and continues until the end of August 2002. Key elements and milestones have been included in the figure. Time requirements are exaggerated to allow for both experiment set-up and concurrent use of facilities by other research projects. Phase one is allotted 6 months, phase two 12 months, and phase three 18 months owing to the increased complexity of the tasks involved in each phase. The entire project is expected to last 36 months.

Facilities and Resources

Essential to the success of this research is the projected use of NASA LeRC resources. LeRC's vacuum chambers and associated diagnostics, machine shops, and technical expertise will be required. In phase one, advice and guidance in designing the ionization chamber will be sought from LeRC researchers and the LeRC machine shops will be used to construct the ionization chamber. Testing can either occur at PEPL, LeRC, or both facilities. Phase two will utilize the machine shops at LeRC to modify the PEPL-70. Benchmarking of the PEPL-70 will be at both LeRC and PEPL. These performance tests will be conducted before and after the modifications to the thruster. Phase three construction of the new thruster will again utilize LeRC machine shops. Benchmarking will be at LeRC and PEPL. The use of both experimental facilities will aid in validating the design, having data from different facilities to compare.

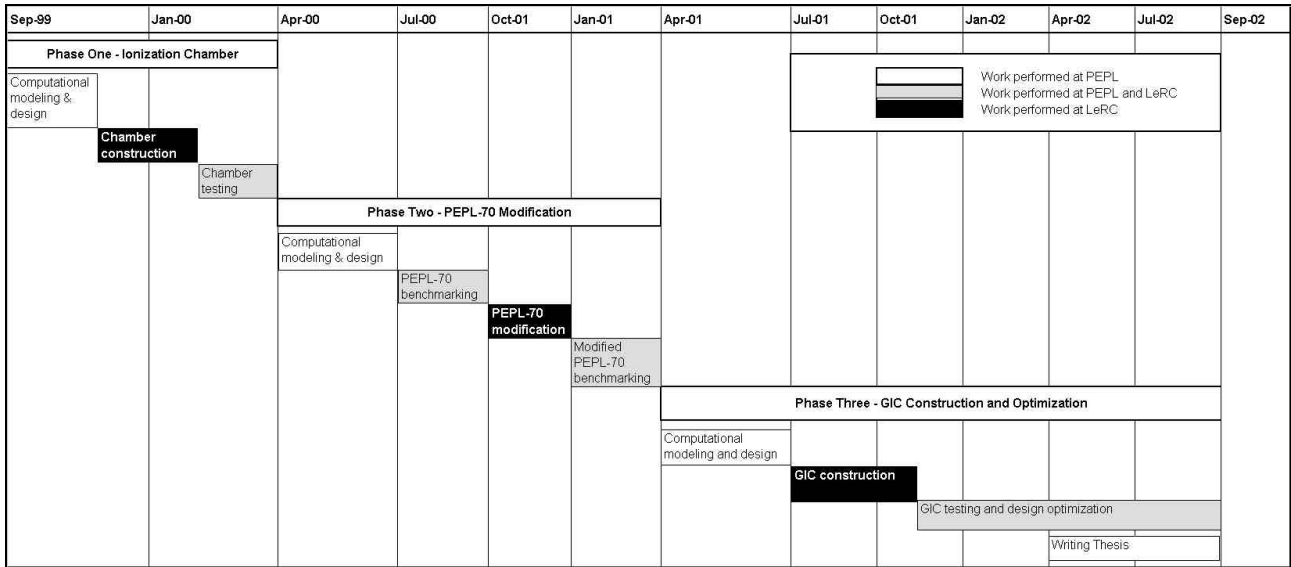


Figure 6 - Schedule of key elements and milestones. Project initiates September 1999 and finishes August 2002.

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