A Proposal to Develop a Double-Stage Hall Thruster for Increased Efficiencies at Low Specific-Impulses

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Abstract

The development of a double-stage Hall thruster to improve thruster efficiency at low specific impulses, while maintaining high efficiencies at large specific impulses is proposed. The additional electrode configuration and composition for the double-stage Hall thruster will be investigated using computer analysis codes and proof of concepts. As well, the modified magnetic field topography necessary for a double-stage Hall thruster will be investigated and optimized using computer analysis codes. Modification of the 1-kW class closed-drift Hall thruster developed at the PEPL, the PEPL-70, will be based on the initial design criteria developed from the computational analysis and bench top experiments of the double-stage Hall thruster. Two possible electrode materials, which have good electron emittance, will be investigated for the use as a middle electrode; these materials are impregnated porous tungsten (4:1:1 molar ratio of BaO, CaO, and Al_2O_3) and lanthanum hexaboride (LaB_6). The proposed research begins in July 1999 and concludes in July 2002.

Objectives

The purpose of this proposed project is to develop a Hall thruster, or a modification to an exiting thruster, that is capable of achieving greater efficiencies at lower specific impulse (1000-1300 seconds) than conventional closed-drift Hall thruster while maintaining high efficiencies at large specific impulses (>1300 seconds). A Hall thruster that consists of one region where ionization and ion acceleration takes place is known as a single-stage device. This single-stage Hall thruster requires an electron back flow to establish ion acceleration and ionization of the neutral propellant gas. The generations of ions in the same region as the acceleration of the ions leads to one of the major efficiency loss mechanisms for a Hall thruster operating at low specific impulse[1]. The efficiency loss at specific impulses ranging from 1000-1500 seconds is due to the fact that the majority of the thruster's discharge voltage is devoted to ionization and not acceleration. The goal of this proposed research is to investigate the idea of de-coupling the ionization and acceleration regions of a Hall thruster. This two-region concept is known as a double-stage Hall thruster and has been investigated by Russian[2] and Japanese[3] researchers. The idea behind a double-stage configuration is to provide an additional electrode between the anode and the cathode/neutralizer of a typical Hall thruster. The ionization stage can be designed to operate at a fixed power for a given propellant flow rate, thus ensuring a predictable ionization fraction of the propellant. The acceleration stage, being de-coupled from the ionization process, can be designed to maximize the acceleration of the ions entering this region. The optimization of the acceleration stage can evolve magnetic field and channel length adjustments.

To gauge improvements of the double-stage Hall thruster over a conventional single-stage closed-drift Hall thruster, the total efficiency of the double-stage thruster (η_t) will be developed and investigated. The total efficiency of the double-stage Hall will scale like the following expression[2], equation (1).

$$h_t \propto \frac{1}{\left(1 + {I_d V_d}/{I_a V_a}\right)} \qquad (1)$$

In this equation, the discharge current and voltage as well as the acceleration current and voltage play a major role in determining the double-stage Hall thruster's efficiency.

Theory

A single-stage Hall thruster is a coaxial plasma device in which a magnetic field, which is produced by electromagnetic solenoid coils or permanent ferromagnetic core pole pieces, effectively traps electrons in the acceleration channel. The trapped electrons provide an ionization region for the thruster propellant. A basic schematic of a single-stage Hall thruster device is presented in Figure 1[4].

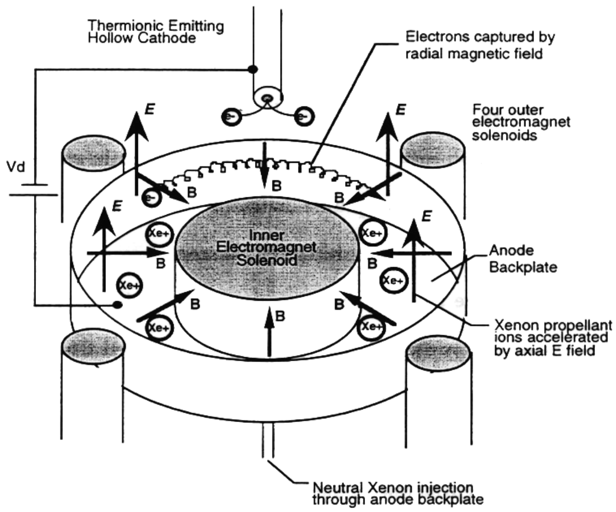


Figure 1, Schematic Illustrating the Physics of Operation of a Single-Stage Hall[4]

The electromagnetic or ferromagnetic configuration of a single-stage Hall thruster results in an essentially radial magnetic field topography with peak fields on the order of a few hundred-gauss. An axial electric field is developed between the anode and the thermionic emitting cathode. Electrons emitted from the cathode are then accelerated towards the anode. However, before the electrons can reach the anode, they experience an **E**x**B** azimuthal drift, creating what is known as the Hall current. The Hall current in the azimuthal direction effectively impedes the electron motion towards the anode. The trapped electrons act as the ionization source, through collisions with neutral propellant particles, for the single-stage Hall thruster. The propellant ions have greater masses than the electrons, therefore, the radial magnetic field has little to no effect on the acceleration trajectory of the propellant ions. The ionized propellant is then accelerated through the potential held by the electrodes. Due to the trapped electrons suppressed axial mobility, the plasma in the acceleration region of the Hall thruster can support a large axial potential close to the applied voltage across the electrodes.

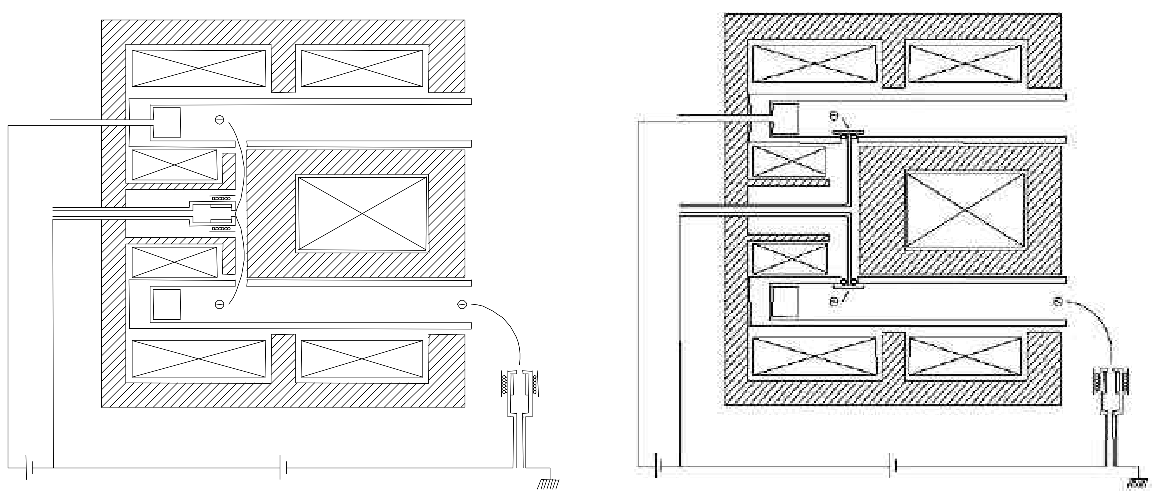


Figure 2, Simple sketches of two possible double-stage Hall Thruster Configurations.

The proposed double-stage Hall thruster will de-couple ionization and acceleration of the propellant into two stages. A basic schematic of two possible double-stage Hall thrusters is presented in Figure 2. The double-stage Hall thruster will incorporate a three-electrode configuration. In the ionization stage, a fixed potential between an annular anode and middle electrode/cathode will regulate the ionization of the propellant depending on the flow rate of the neutral propellant. The middle electrode will be made of impregnated porous tungsten (4:1:1 molar ratio of BaO, CaO, and Al_2O_3) or lanthanum hexaboride (LaB_6). The primary role of the middle electrode will be to generate a constant discharge voltage with the anode and to provide a predictable electron source for propellant ionization. The acceleration stage of the proposed thruster is the region between the downstream neutralizer/cathode and the middle electrode, which acts as the anode of the acceleration region. Now that the ionization process has been removed from the acceleration region, possible adjustments to the magnetic and electric field topography can be implemented to enhance the ion acceleration process. Theoretically, since the ionization process is separated, the majority of the ions entering the acceleration stage will have approximately the same energy and gain a uniform acceleration energy. Another possible advantage gained by the double-stage configuration is that by de-coupling the neutralizer from the ionization process, the proposed double-stage Hall thruster may not require the same amount of electrons to sustain the discharge. Thus, lower operating power levels of the neutralizer may be feasible.

The Double-stage Hall thruster concept has been worked in the past by Yamagiwa[3], of Japan, and Tverdokhlebov[2], of Russia, with promising results. The double-stage Hall thruster concept that Yamagiwa developed and tested in the late 1980's was based on a closed-drift acceleration region with an annular insulator slit separating the thermionoc emitting middle electrode from the anode in the ionization region. In this investigation, Yamagiwa established and compared the propellant utilization efficiency versus ion production cost, as well as the thrust and total efficiency versus specific impulse for both a single-stage and double-stage Hall thruster. These characterizations are presented in Figure 3a & 3b. Note that the evaluation test performed by Yamagiwa was conducted using Argon as the propellant and that the acceleration region of their Hall thruster was not modified between the single and double-stage testing.

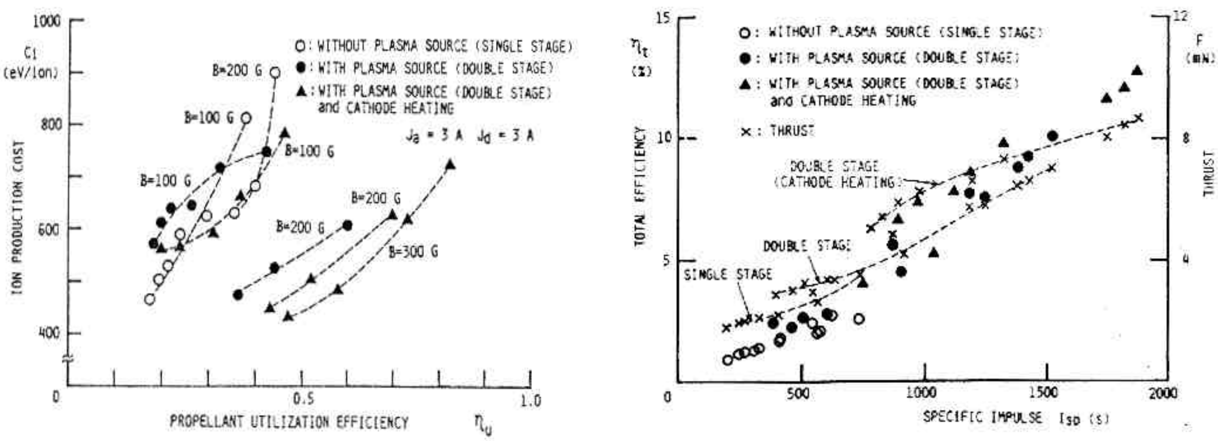


Figure 3a & 3b, **Propellant Utilization Efficiency versus Ion Production Cost and Total Thruster Efficiency versus Specific Impulse[3].**

The double-stage anode layer Hall thruster developed by Tverdokhlebov[2] also employs the idea of separating the ionization region from the acceleration region, as proposed in this project. However, the Russian design still requires electron back flow from the acceleration stage to maintain ionization. Thus, the Russian double-stage Hall thruster design still experiences the same efficiency loss term as a single-stage Hall thruster. Theoretical investigation into the possible advantages of the double-stage anode layer Hall thruster have been conducted in the past by Antipov[1,6], which shows the potential of the double-stage Hall thruster concepts. A comparison of the theory and experimental thrust efficiency versus specific impulse for a double-stage anode layer Hall thruster is presented in Figure 4.

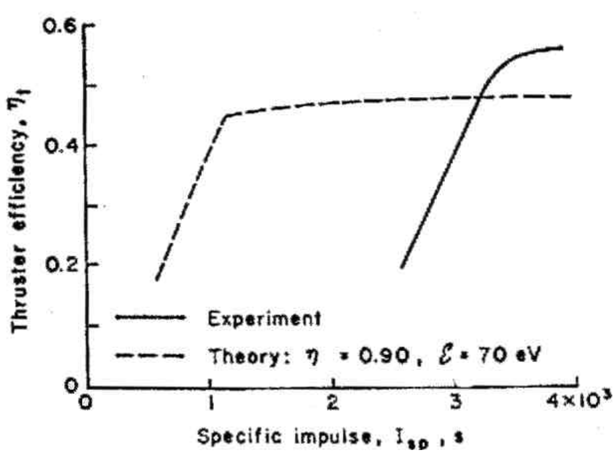


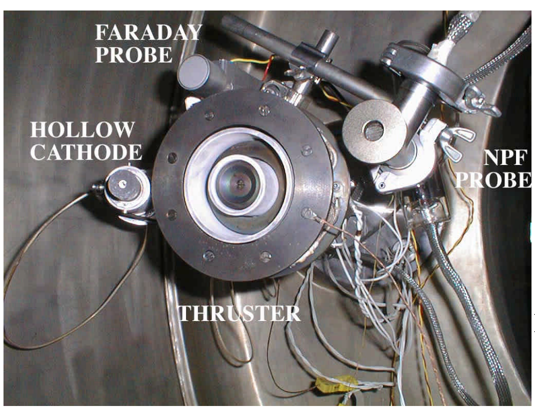
Figure 4, **Theory and experimental thrust efficiency versus specific impulse for a double-stage anode layer thruster[1,6]**

Methodology

The proposed method of achieving the goal of increasing the efficiency of a closed-drift Hall thruster by de-coupling the ionization region from the acceleration region will be approached in six phases. The initial phase will involve a computational and experimental investigation of the basic design consideration of the double-stage Hall thruster. The second phase of this proposed project will incorporate a computational analysis of the double-stage Hall thruster. In the third phase of this project, the University of Michigan PEPL-70 1kW closed-drift Hall thruster will be modified to meet the design requirements found in the first two phases. After the PEPL-70 is modified to meet the double-stage design, the fourth phase of the project will investigate the basic operating characteristics of the new thruster design concepts in the University of Michigan's Large Vacuum Test Facility (LVTF) and vacuum facilities at NASA LeRC. The fifth phase of this project will encompass an update to the computational models and any final design modification to the double-stage PEPL-70 Hall thruster based on the initial experimental results obtained in the fourth phase of the proposed project. Finally, in the last phase of the project, the double-stage PEPL-70 Hall thruster will undergo extensive testing at NASA Lewis research center.

In the first and second phase of the proposed project, several basic design concepts for a double-stage Hall thruster will be investigated. This investigation will begin by examining the basic design equation[5] for a closed-drift Hall thruster in a single stage configuration. Then applying concepts discussed in the previous articles on double-stage Hall thrusters[2,3] and the ideas developed at PEPL, several double-stage Hall thruster design concepts will be defined. By employing several in house computational tools such as QuickField™*, a $2^1/_2$ dimensional magnetic field code, and Magic™, a two and three dimensional particle in a cell code developed by Mission Research Corporation, in the development of the double-stage Hall thruster, the electron and ion distribution functions and trajectories will be investigated in both the ionization and acceleration stages of the proposed thruster to determine preliminary design concepts.

The third phase of the project consists of modifying the PEPL-70 single-stage closed-drift Hall thruster. A picture and cross-sectional schematic of the PEPL-70 are presented in Figures 5a & 5b. Once the preliminary design conditions are finalized, a cost estimate and materials required to perform the modification on the PEPL-70 will be compiled. Then at least two separate ionization and acceleration regions will be constructed based of the information learned in the first two phases. Each stage variation will be derived from the optimization of the magnetic and electric topography that is believed to maximize the principal operations of each stage.



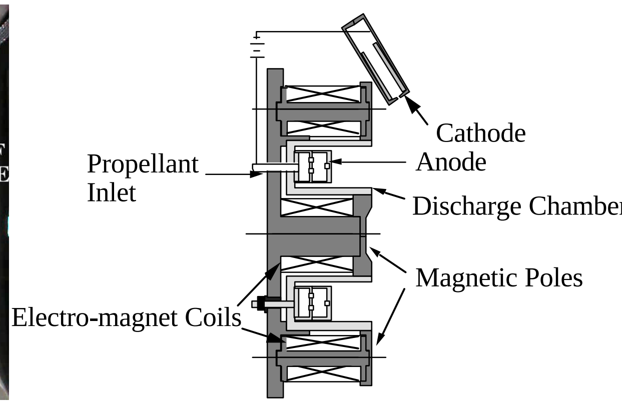


Figure 5a & 5b, A picture and cross-section of the PEPL-70 single-stage Hall thruster.

Preliminary testing of each proposed design concept will be performed, in the fourth phase of the project, at the University of Michigan LVTF and NASA LeRC. Experimental diagnostic equipment available in the LVTF laboratory include Langmuir probes, Retarding Potential Analyzer, Faraday Probe, Neutral Particle Flux Probe, Heat-Flux Probe, Optical Emission Spectroscopy, a Molecular Beam Mass Spectrometer, and a thrust stand.

* Computational code used to design the magnetic circuit for the 5kW PEPL-170 closed-drift Hall Thruster[7]

Incorporating the plasma diagnostic capabilities of the LVTF and NASA LeRC, a good understanding of the performance capabilities of the preliminary double-stage Hall thruster design will be established.

Once the initial performance testing of the new double-stage Hall thruster concepts are compiled and interpreted, the fifth stage of the proposed project will comprise of updating the computational model and design criteria of the double-stage PEPL-70 Hall thruster. In the sixth phase of the project, the final design of the double-stage PEPL-70 Hall thruster will be installed and evaluated at the NASA LeRC Electric Propulsion Laboratory. These thruster evaluation tests at the NASA LeRC will help determine if the double-stage configuration developed during this project will significantly increase the total efficiency of the thruster at low specific impulse ranges.

References

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Facilities and Resources

To build the components necessary for modifying the PEPL-70 Hall thruster and to evaluate the performance of the new double-stage engine, the machine shop, vacuum facilities, and personnel at NASA LeRC will be required.

Research Timeline