PPPL digest
PRINCETON PLASMA PHYSICS LABORATORY
A United States Department of Energy Facility
DECEMBER 2004

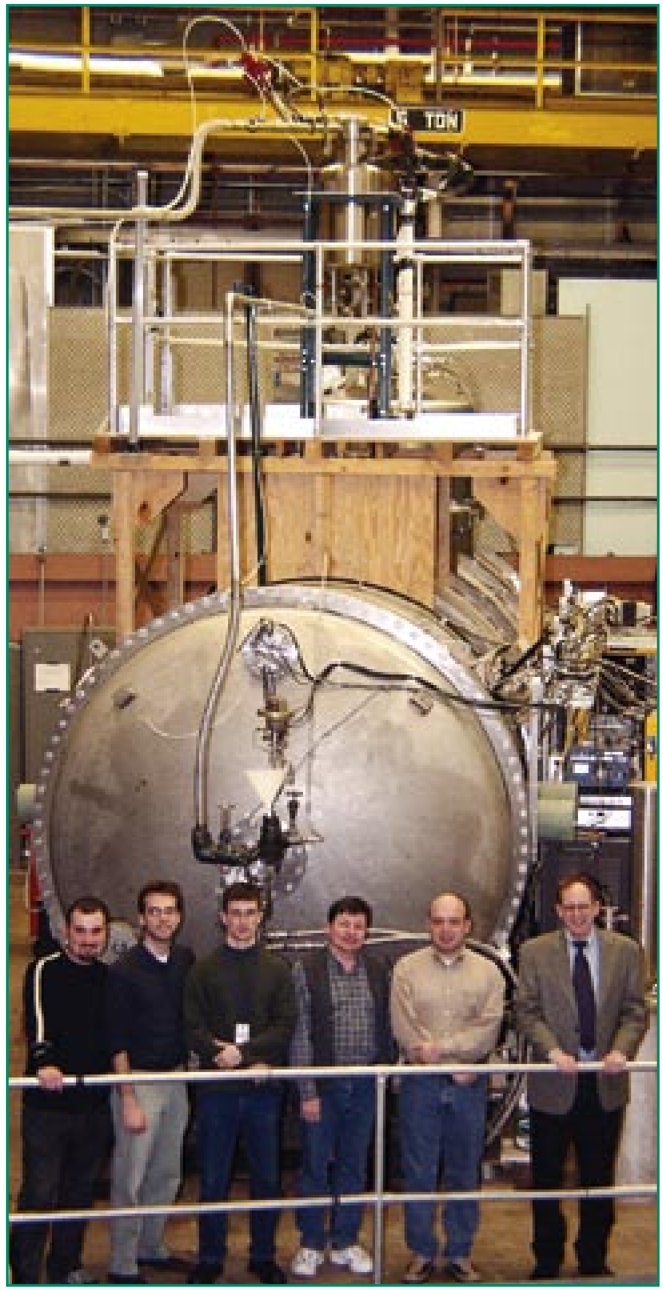
Hall Thruster Experiment Underway at PPPL

The Hall Thruster is a plasma-based propulsion system for space vehicles. The amount of fuel that must be carried by a satellite depends on the speed with which the thruster can eject it. Chemical rockets have very limited fuel exhaust speed. Plasmas can be ejected at much higher speeds, therefore less fuel need be carried on board. During the past quarter century, the Russians placed in orbit about 100 Hall Thrusters. However, the vast majority of satellites worldwide have relied on chemical thrusters and, to a lesser extent, ion thrusters.

In 1999, a Hall Thruster Experiment was established at the Princeton Plasma Physics Laboratory (PPPL). The PPPL experiment itself resulted from a collaborative theoretical research effort with the Center for Technological Innovation at Holon, Israel. This study, funded by the U.S. Air Force, identified improvements that might make Hall Thrusters more attractive for commercial and military applications.

Hall Thruster Operation

A conventional ion thruster consists of two grids, an anode and a cathode, between which a voltage drop occurs. Positively charged ions accelerate away from the anode toward the cathode grid and through it. After the ions get past the cathode, electrons are added to the flow, neutralizing the output to keep it moving. A thrust is exerted on the anode-cathode system, in a direction opposite to that of the flow. Unfortunately, a positive charge builds up in the space between the grids, limiting



The PPPL Hall Thruster Experiment and research team.

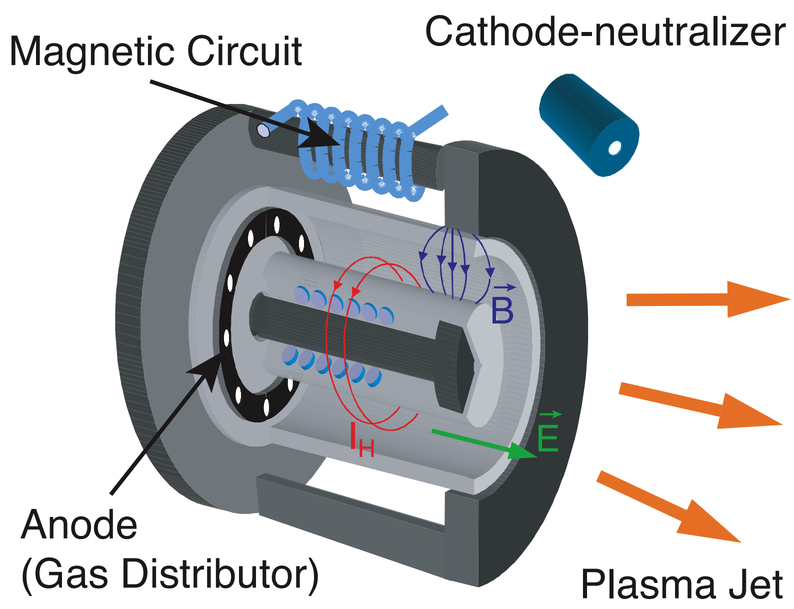


Figure 2. The Hall Thruster concept.

the ion flow and, therefore, the magnitude of the thrust that can be attained.

In a Hall Thruster, electrons injected into a radial magnetic field neutralize the space charge. The magnitude of the field is approximately 200 gauss, strong enough to trap the electrons by causing them to spiral around the field lines. The magnetic field and a trapped electron cloud together serve as a virtual cathode (see illustration above). The ions, too heavy to be affected by the field, continue their journey through the virtual cathode. The movement of the positive and negative electrical charges through the system results in a net force on the thruster in a direction opposite that of the ion flow.

Applications

Thrusters are used to compensate for atmospheric drag on satellites in low-earth orbit, to reposition satellites in geosynchronous orbit, or to raise a satellite from a lower orbit to geosynchronous orbit. For each kilogram of satellite mass it turns out that about one or two watts of on-board power are available. At PPPL we have now built Hall thrusters ranging from below a hundred watts to more than 2 kilowatts. PPPL physicists hope that their ideas can be useful both for thrusters operating at many thousands of watts, like for planetary missions, as well as, in the small power limit, for very small satellites with masses of 50 to 100 kilograms.

Hall Thruster Propellant

Plasma thrusters for current space applications employ xenon propellant. Xenon is relatively easy to ionize and store onboard the spacecraft. It also has a high atomic number (54), which means a lot of mass per ionization energy expended. The ionization energy is an unavoidable inefficiency; in the range of exhaust velocities most useful for current space applications – about 15 km/sec – this energy loss for once-ionized xenon is less than 10 percent of the exhaust energy. (If the weight per atom were half, this percentage would double.)

Installation

The site of the former PPPL S-1 Spheromak Experiment was selected for the Hall Thruster Experiment. Facility work began with the relocation of the 15-ton, 28-foot by 8-foot manipulator tank, previously constructed for use on the Tokamak Fusion Test Reactor. The vessel is now being used as the vacuum chamber for the Hall Thruster Experiment. PPPL's state-of-the-art prototype Hall Thruster was then assembled inside the vacuum chamber along with a complete set of diagnostics.Initially, less than

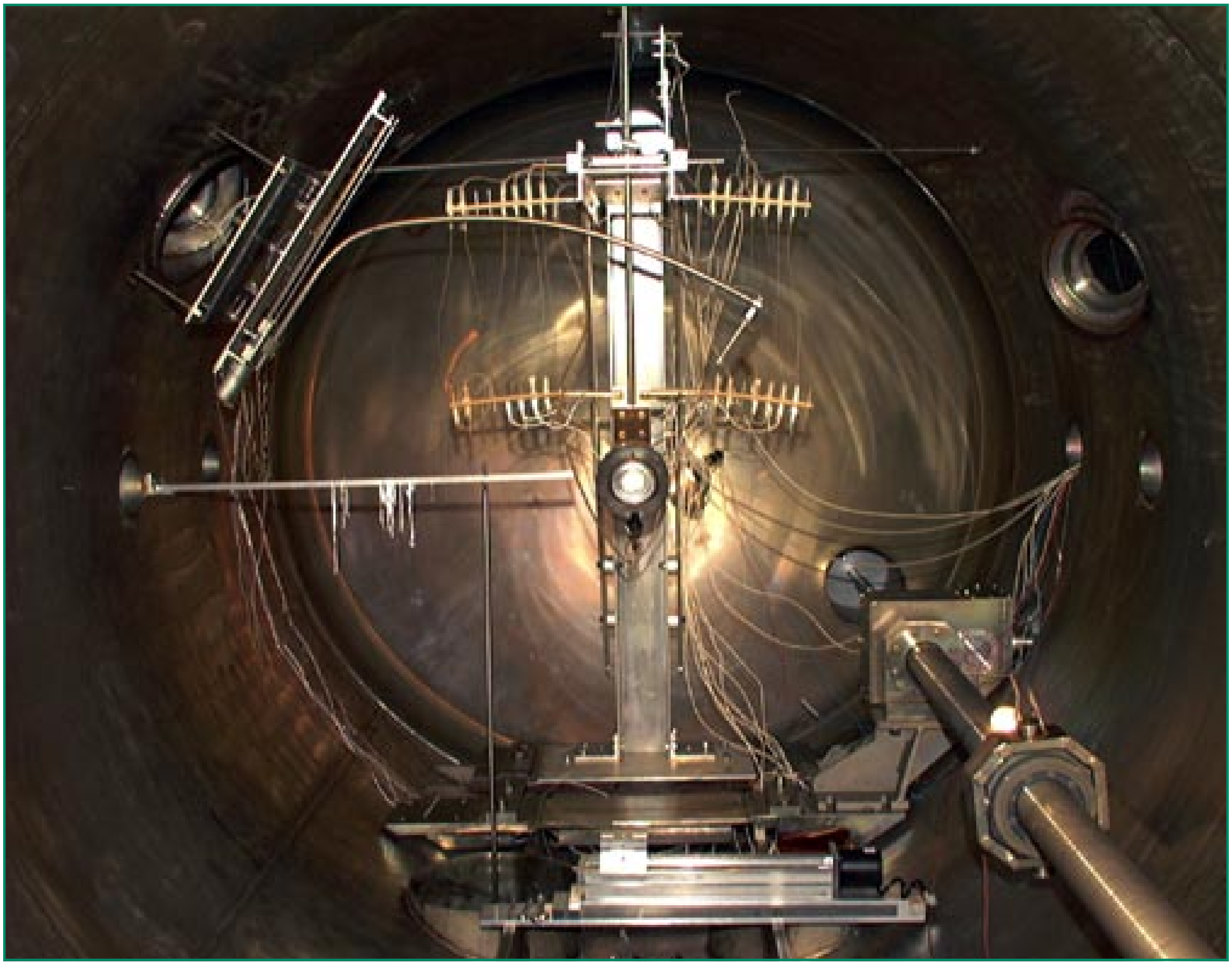


Figure 3. Interior view of the PPPL Hall Thruster.

$200,000 was spent to assemble the PPPL's Hall Experiment. With the help of grants from the New Jersey Commission of Science and Technology, as well as from DARPA and the Air Force, this experiment has now been upgraded to include cryogenic pumping, making it a state-of-the-art facility.

PPPL Hall Thruster Results

PPPL's Hall Thruster was designed with a modular configuration to allow multiple thruster geometries that could be diagnosed in detail easily. This includes the ability to measure precisely in three dimensions how the thrust varies with position. This information can be used to arrive at techniques to narrow the plume and obtain more control over the outflow from the thruster, possibly improving its efficiency. A small plume divergence is a very important design feature for facilitating integration of the thruster in a spacecraft.

Initially PPPL's Hall Thruster operated at 900 watts with an efficiency equivalent to state-of-the-art thrusters. The thruster was then modified to a segmented configuration. Each segment was held at a specific electric potential, enabling researchers to control exactly where the voltage drop occurred along the length of the thruster. In a low mass-flow-rate situation, segmented thruster operation lead to narrowing of the plume by as much as 20 degrees. Since then, detailed and unique measurements of the electrical potential were made in the physically-chal-

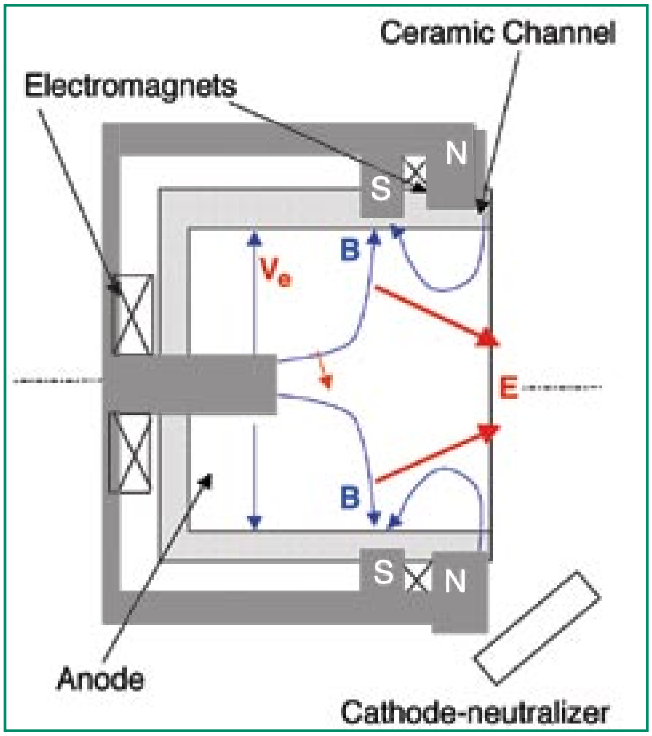


Figure 4. Schematic of the Hall Microthruster now under development.

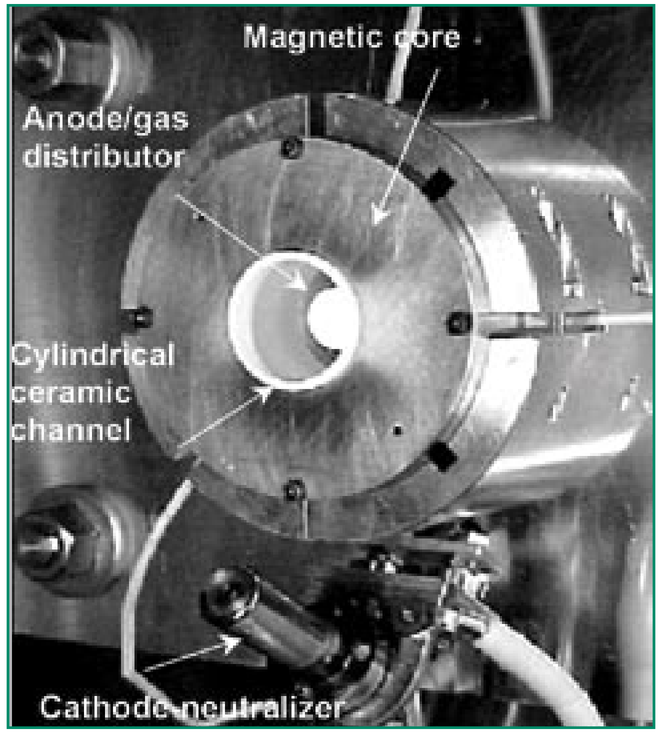


Figure 5. The new Hall Microthruster.

lenging interior of the Hall Thruster. The potential distribution was shown to be correlated to the plume divergence. Moreover, in 2004, it was shown that the emission properties of the segmented electrodes could affect the electron current, suggesting important regimes for high-efficiency operation.

PPPL Hall Microthruster Results

In addition to imagining larger, more powerful thrusters capable of accelerating satellites more quickly or powering larger satellites, scientists also envision a large satellite disbursing hundreds of smaller ones for the exploration of a planet or as a space-based radar array. The PPPL Hall Microthruster was invented to scale to low power. This device employs a cylindrical rather than the conventional annular acceleration configuration. Because of its low surface to volume ratio, the cylindrical geometry is better adapted for microthruster operation. The technological problems associated with scaling to low power are by no means straightforward. The power density tends to grow at small sizes, and the smaller features are more susceptible to heat loading. In attacking these technological constraints, in the cylindrical design, the central magnetic pole is almost eliminated, as shown in Figures 4 and 5. The PPPL Hall Microthruster has now operated below the 100-watt range, useful for very small satellites with masses of 50 to 100 kilograms. Efficiencies in the range of 30% for 100-watt operation were attained, surpassing present-day microthruster technology. Recently, using unique plasma diagnostics inside the channel of the PPPL Hall Microthruster, several interesting phenomena were discovered, including a density peak near the thruster axis. In 2004, by optimizing the magnetic field configuration, a high-efficiency regime was identified at about 150 W.

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The Princeton Plasma Physics Laboratory is a United States Department of Energy Facility engaged in the development of magnetic fusion energy. It is funded by the U.S. Department of Energy (DOE) under contract DE-AC02-76CHO3073.