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Presented at the
1999 Cryogenic Engineering and
International Cryogenic Materials Conference
Montreal, Quebec, Canada

July 12-16, 1999

Prepared at
Oak Ridge National Laboratory
Post Office Box 2008
Oak Ridge, TN 37831-6285 USA

Managed by
LOCKHEED MARTIN ENERGY RESEARCH, INC.
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U.S. DEPARTMENT OF ENERGY
under contract DE-AC05-96OR22464

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*Research supported by the National Aeronautics and Space Administration under Interagency Agreements, D.O.E. #2044-AA18-Y1 and NASA #T-7139V.

**Managed by Lockheed Martin Energy Research Corp. for the U.S. Department of Energy under contract number DE-AC05-96OR22464.

HTS MAGNETS FOR ADVANCED MAGNETOPLASMA SPACE PROPULSION APPLICATIONS*

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ABSTRACT

Plasma rockets are being considered for both Earth-orbit and interplanetary missions because their extremely high exhaust velocity and ability to modulate thrust allow very efficient use of propellant mass. In such rockets, a hydrogen or helium plasma is RF-heated and confined by axial magnetic fields produced by coils around the plasma chamber. HTS coils cooled by the propellant are desirable to increase the energy efficiency of the system. We describe a set of prototype high-temperature superconducting (HTS) coils that are being considered for the VASIMR (Variable Specific Impulse Magnetoplasma Rocket) thruster proposed for testing on the Radiation Technology Demonstration (RTD) satellite. Since this satellite will be launched by the Space Shuttle, for safety reasons liquid helium will be used as propellant and coolant. The coils must be designed to operate in the space environment at field levels of 1 T. This generates a unique set of requirements. Details of the overall winding geometry and current density, as well as the challenging thermal control aspects associated with a compact, minimum weight design will be discussed.

INTRODUCTION

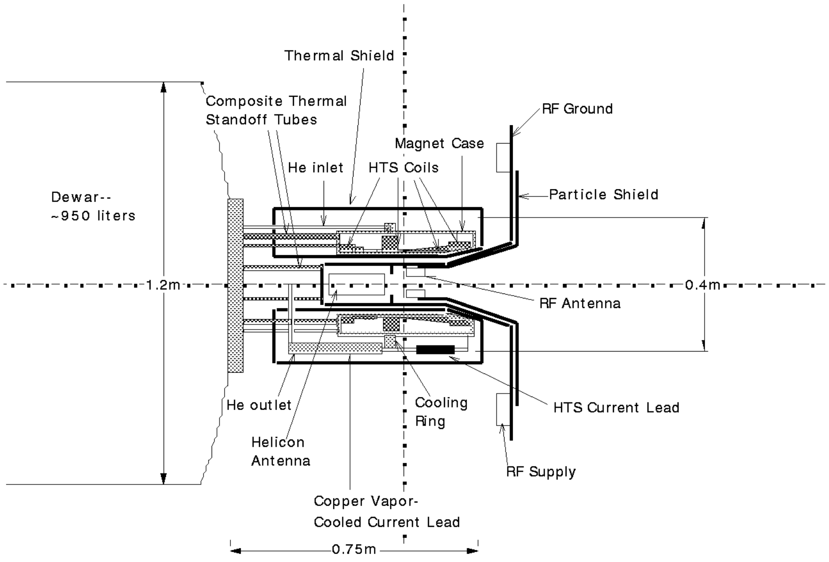
Conventional chemical rocket engines for space applications have limited ability to modulate thrust. Consequently, the spacecraft trajectory is controlled by alternately firing the engine for a short time and coasting for long periods. For interplanetary missions, this can lead to very long transit times that would be impractical for human space exploration. If spacecraft speed is increased to shorten the mission, the propellant is used less efficiently, leading to much greater initial launch weight and mission cost.

The thrust in a rocket engine is the product of propellant mass flow and relative exhaust velocity. If these two parameters can be independently controlled, they can be modulated during the mission to produce a much shorter transit time with a given amount of propellant than with a conventional engine. If the engine is operated at constant power, it can be shown[1] that increasing the exhaust velocity and decreasing the propellant mass flow in the middle of the trajectory leads to minimum propellant usage. The VASIMR thruster[1] is one way of accomplishing this exhaust modulation. In this concept, an RF-heated plasma is constrained to stream out of a magnetic nozzle at very high exhaust velocities. The thrust and exhaust velocity can be varied by controlling the inlet mass flow, plasma parameters, and magnetic field. A collaboration between NASA–Johnson Space Center, Oak Ridge National Laboratory (ORNL), University of Texas-Austin, University of Maryland, and MSE Technology Applications is underway to develop such a thruster for the Radiation Technology Demonstration (RTD) satellite, which may be launched as early as 2002. This satellite will be launched into low earth orbit by the Space Shuttle, and will then use electric propulsion by either the VASIMR or a Hall thruster to spiral out to a distance of 5 earth radii. Along the trajectory, it will release several small micro-satellites that will monitor radiation levels in the Van Allen Belts. ORNL is performing theoretical and experimental plasma studies in support of the VASIMR project, as well as studies on the development of its superconducting magnetic nozzle and confinement systems that are the subjects of this paper.

MAGNET CONFIGURATION

Figure 1 shows an overall schematic of the VASIMR thruster. Since the RTD satellite will be launched by the Space Shuttle, for safety reasons liquid helium will be used as both propellant and magnet coolant. In principle this would allow conventional Nb-Ti coils for the magnet, but since the ultimate goal is the use of hydrogen propellant for interplanetary missions, NASA wants an early demonstration of an HTS magnet in the spacecraft.

The thruster assembly is supported off the aft end of the liquid helium (LHe) dewar by low-conductivity composite tubes. The magnet coils are built up from a set of nested cylindrical solenoids. The coils are well isolated from the hot plasma chamber by multi-layer insulation. Cold He vapor enters the aluminum magnet case at a chill ring located midway along its axis over the highest-field coil. If needed, a cryocooler can be tied to this ring to provide additional refrigeration. Cold vapor will exit at roughly 30 K. It will then cool a set of HTS current leads and an intermediate shield to less than 80 K. Finally, it will cool a set of vapor-cooled copper leads before entering the plasma chamber at roughly room temperature. The coil set has four main sections. The helium inlet end of the plasma chamber contains a RF antenna to ionize the helium and form the plasma. The low-field ion source coils surround this area. A choke coil that produces a maximum magnetic field of 0.8 T on axis is located downstream of the ion source section. The next section surrounds another RF antenna that further heats the plasma ions to 100 eV by ion cyclotron resonance heating (ICRH). The last section is the nozzle area, where the hot plasma exhaust exits the thruster. All four sections will be connected in series. The expected thrust is about 0.2 N.



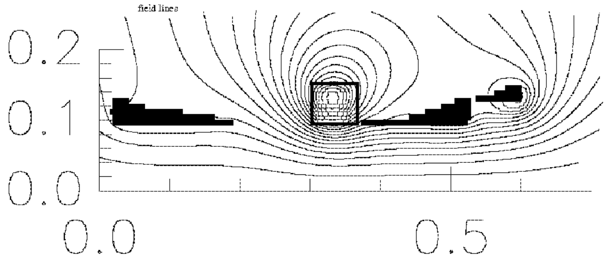


Figure 2. VASIMR thruster coils and magnetic flux lines. Axis units are meters.

General Requirements

The magnet must be able to withstand the Space Shuttle's 3-g launch load, as well as vibration which peaks in the 125-300 Hz range. It must be resistant to the radiation levels that occur in the Van Allen Belts over a mission duration of a few months. This issue is probably more important for the magnet insulation than the HTS material. During the times that the RTD satellite will be in the Earth's shadow, solar power for the magnet power supply will not be available. A persistent switch is therefore desirable. The magnet windings must be accurately constructed to give a field error of less than 1%. The target mass is 20 kg.

DESIGN CALCULATIONS

Magnetic Field Calculations

Figure 2 shows a detail of the coils along with calculated flux lines. The coils contain about 200,000 Amp-turns, with a nominal operating current of 60 A. The overall winding current density is 2.5 kA/cm^2 in the low-field ion source section and 5 kA/cm^{2}in the remaining sections. These values were chosen so as to be within the limits achievable by existing commercial Bi-2212 coated conductors or Bi-2223 PIT conductors operating in the neighborhood of 30 K.

Detailed field calculations were made using the ORNL code SOLE. This code uses current density distributions rather than current filaments, and is accurate within the windings as well as in free space. Table 1 shows the maximum radial and axial field components in each section of the magnet. The axial fields determine the maximum hoop stress in the conductor. The radial fields (which are perpendicular to the HTSC tape and limit its current density) are used along with manufacturer conductor specifications to verify that the conductor has the specified current density.

Mechanical Loads on Winding

The axial attractive forces between the coils are reacted by the coil mandrel. These forces were calculated with the code LF2COAX, by P.L. Walstrom[2]. These forces are as follows:

Table 1. Maximum magnetic fields in winding sections.

Magnet Section	Max. Radial Field (T)	Max. Axial Field (T)
Ion source	0.24	0.29
Choke	0.79	1.19
ICRH	0.31	0.69
Nozzle	0.56	0.65

1. Between the ion source section and the choke section— 578 N (130 lb)
2. Between the choke section and the ICRH section— 4467 N (1003 lb)
3. Between the ICRH section and the nozzle section— 3646 N (818 lb)

The mandrel section where the maximum axial force of 4467 N is exerted is about 25 cm long and 19 cm in diameter. For a short column such as this, failure occurs by compressive stress in the material. By this criterion, even a 1-mm mandrel wall thickness would easily handle the compressive load, given a material with at least 34 MPa (5000 psi) working compressive strength. The ultimate compressive strength of G-10 fiberglass edgewise to the laminations, for example, is 320 MPa (47,000 psi)[3]. However, if the mandrel is the inside wall of the magnet case, it is under external pressure. Standard ASME Pressure Vessel Code calculations indicate that an aluminum mandrel would need to be about 1.5 mm thick to withstand 1 atm in the vacuum of space.

The winding hoop stress at radius R is given by

$$\sigma = R\, J_{cond} B_z \ , \qquad (1)$$

where J_{cond} is the conductor current density and B_z is the local axial field. At the point of maximum axial field in the choke coil, B_z = 1.19 T and R = 0.095 m. If the conductor packing fraction in the winding is 70%, then J_{cond} is 71.4 MA/m^2. The maximum hoop stress is then 8.1 MPa (1171 psi). This is well within strain limits for commercial HTS conductors, even without considering any support from fiberglass and epoxy impregnating the windings.

Heat Loads

The refrigeration available for cooling the magnet is stringently limited by the 3.3-mg/sec flow of helium gas needed to operate the thruster. Since the LHe dewar alone would normally boil off much more than this, it is expected that the dewar will have an actively cryocooled shield. About 140 J/gm of sensible heat is available for cooling the magnet with a He gas inlet temperature of 4.4 K and an outlet temperature of 30 K. This allows a total heat load of 0.46 W on the magnet. The major heat loads are:

1. Joule heating from residual resistance and joints in the conductor,
2. Conduction through the magnet supports,
3. Heat flow through the superinsulation,
4. Heat flow through the current leads.

Design calculations have been performed to allocate about 0.1 W to each of these heat loads.

Winding Resistance. The total length of conductor in the winding is over 3000 m. This would generate over 18 W at 60 A with operation near the critical current at 1 μV/cm. The conductor voltage is proportional to I^n. An *n*-value of at least 10 is necessary to allow operation at 60% of critical current. This would limit resistive heating in the conductor to 0.1 W. Joints in the winding will need to be minimized and be of very low resistance.

Support Conduction. The magnet would be supported from a baseplate on the LHe dewar by composite tubes to minimize heat leak. To limit the support loads to about 0.1 W, three G-10 tubes of diameter 2.54 cm, length 20 cm, and thickness 1.7 mm could be used. A heat sink at 77 K would be needed about halfway along the tubes. Support tubes with larger diameter or thickness would need to be made of advanced low-conductivity carbon composites.

Superinsulation. The area of the inner surface of the magnet case that faces the warm plasma chamber is about 0.38 m^2. Recent measurements[4] on evacuated multilayer insulation (MLI) indicate that a practical effective conductivity is about 0.2 mW/m-K. An intermediate shield cooled by the helium vapor is assumed between the magnet case and the plasma chamber. For simplicity, assume that this shield has a linear temperature gradient along its axis from 30 K to some intermediate temperature T_i. Then the average temperature differentials can be used to calculate the heat conducted from the 300-K surface to the shield and from the shield to the magnet. The difference between these heat loads is the heat absorbed by the He vapor as it passes through the shield, warming from 30 K to T_i. If the MLI on each side of the shield is 1 cm thick, T_i comes out to 72 K and the heat load on the magnet is about 0.16 W. However, it must be considered that the outer circumference of the magnet may also be facing a warm surface, which could more than double this heat load. This could be alleviated by installing a much thicker MLI blanket around the outer circumference of the magnet, where more room is available.

Current Leads. To minimize heat loads, commercial HTS leads will be used in the temperature range between the shield and magnet. The vapor from the shield will be used to cool copper leads that extend to the room-temperature power supply buss. Commercial 60-A HTS leads are available with heat loads below 0.03 W per pair. The HTS leads will need to be mounted in a low-field area, and their ability to handle the Shuttle launch and vibration loads needs to be verified.

The copper leads have not been analyzed in detail. However, following Iwasa's[5] demonstration, in the "high" current limit where the thermal gradient along the lead is determined mainly by Joule heating, the heat transferred out of the cold end at temperature T is

$$Q(T) = \frac{\kappa(T)\rho(T)I^2}{\dot{m}C_p(T)} \tag{2}$$

where the thermal conductivity κ, resistivity ρ, and specific heat C_p are evaluated at the bottom end temperature of 72 K. With a mass flow of 3.3 mg/sec, this relation gives 0.25 W per lead. This 0.5 W is in addition to the MLI heat load on the shield. At a mass flow of 3.3 mg/sec, it could raise the shield temperature by another 29 K, too high for operation of the HTS lead.

Mass

The winding mass will depend on the conductor chosen. The winding contains about 3040 m of conductor. On the basis of current commercial conductors known to the authors, a conductor mass of about 15 kg is estimated. This leaves 5 kg for the remaining insulation and structure. Clearly, lightweight structural materials such as advanced composites will be required.

CONCLUSION

The preliminary calculations summarized above suggest that a HTS coil would be feasible for an advanced magnetoplasma thruster. However, the desired He mass flow appears to be marginal for operation at 30 K. Hopefully, continuing advances in HTS conductor performance will allow operation at higher temperatures. In the future, a more detailed and self-consistent thermal model will be generated to take into account the interactions between the magnet, lead, and shield heat loads. Further investigations will explore alternative plasma configurations and use of liquid hydrogen instead of He.

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