Enhancing VASIMR® with Maturing Technologies

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The VASIMR® engine is set to rise through NASA's technology readiness levels (TRLs) with improvements made possible by recent advances in material science, manufacturing, and other industries. A new power processing unit design will carry Ad Astra Rocket Company's current test article, the VX-200SS™, through TRL-5 by providing features including magnetic shielding and vacuum compatibility. The development of Ad Astra Rocket Company's protoflight system, the TC-1Q™, will be spurred forward to TRL-6 by the integration of a high temperature superconducting magnet. This replacement for the current low temperature superconducting magnet will utilize a second-generation high temperature superconducting wire that loosens thermal and power constraints. One investigation into other technologies determined that even with the recent advancements to the field of additive manufacturing it is not currently practical for producing the frame of the new magnet. Another investigation found that carbon fiber may be a viable mass-reducing option as a base for the magnet's mandrel.

I. Nomenclature

C&DH	=	Command & Data Handling
DC	=	Direct Current
GN&C	=	Guidance, Navigation, & Control
HEL	=	Helicon
HP	=	High Power
HTS	=	High Temperature Superconducting
ICH	=	Ion Cyclotron Heating
LEO	=	Low Earth Orbit
LTS	=	Low Temperature Superconducting
MRI	=	Magnetic Resonance Imaging
PPU	=	Power Processing Unit
RF	=	Radio Frequency
SEP	=	Solar Electric Propulsion
SLS	=	Selective Laser Sintering
TRL	=	Technology Readiness Level
VASIMR®	=	Variable Specific Impulse Magnetoplasma Rocket

II. Introduction

The Variable Specific Impulse Magnetoplasma Rocket (VASIMR®) engine is being developed and tested by Ad Astra Rocket Company (Ad Astra). The VASIMR® engine has the potential to revolutionize in-space

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transportation as an economically efficient high-power (HP) solar electric propulsion (SEP) system. This system is capable of moving large payloads around low earth orbit (LEO), cis-lunar space, and any other regime where the mass tradeoff of solar panels makes solar energy a viable power source. As nuclear power sources become more prominent, the capabilities of the VASIMR® engine will greatly expand as the engine can easily scale with power.

Ad Astra's development program is currently under the NASA NextSTEP contract to advance the VASIMR® engine technology readiness level (TRL) to TRL-5. Achieving TRL-5 signifies that the individual subsystems have been tested in a relevant environment which for Ad Astra means tested in a vacuum. This stage in the development of the VASIMR® engine is set to culminate late in 2018 with the firing of the VX-200SS™ test article at a power level of 100 kW for 100 continuous hours inside Ad Astra's main vacuum chamber at its facility in Webster, TX. To advance to higher TRL levels, the engine needs various upgrades across its subsystems. Many of these upgrades have recently been made possible by innovation in other industries and, as such, are currently being developed for utilization in the VX-200SS™ system while others are being analyzed for further implementation in the TC-1Q™ following the completion of the third year of the NextSTEP contract.

III. TC-1Q™ System Description

Shown in Fig. 1, the TC-1Q™ is Ad Astra's protoflight system identified by a single thruster core with a magnetic quadrupole. This system is comprised of six subsystems: the rocket core, radio frequency (RF) power processing units (PPUs), a high temperature superconducting (HTS) magnet, thermal management, propellant management, and command & data handling (C&DH). The rocket core contains the helicon (HEL) and ion cyclotron heating (ICH) stages where the plasma is created and accelerated, respectively. The RF PPUs convert power from direct current (DC) to the RF that is transmitted to the rocket core. The HTS magnet creates the magnetic field that directs the plasma and creates a buffer between the rocket core components and plasma. The thermal management system removes waste heat from the rocket core and other subsystem components. The propellant management system regulates the flow of propellant into the rocket core. The C&DH controls all TC-1Q™ system functions.

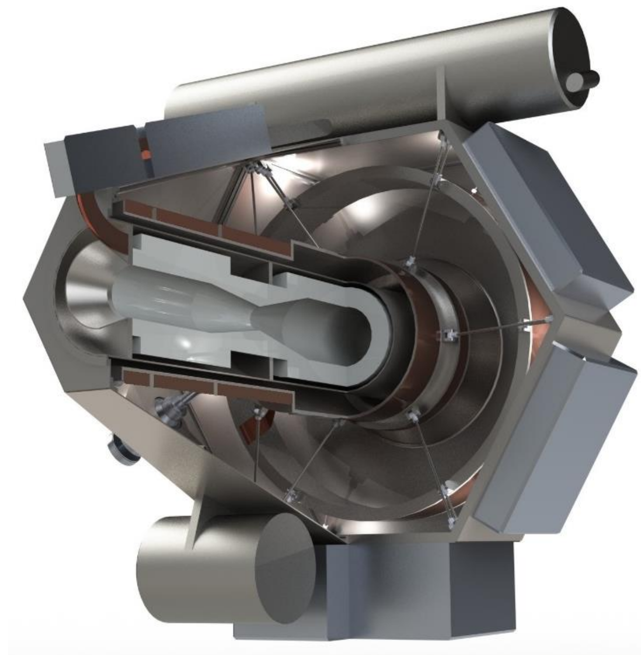

Fig. 1 TC-1Q™ system model

IV. Subsystems

A. HTS magnet

1. High Temperature Superconducting Tape

The VX-200SS™ test article uses a low temperature superconducting (LTS) magnet system designed in 2007 operating at a temperature around 5 K with a maximum field strength similar to that of a typical MRI machine. This LTS magnet system is cryogen-free and has a pressure vessel that allows for operation of the superconducting magnet at atmospheric pressure outside the 150 m^3 main vacuum chamber used in testing. Although never intended for spaceflight, the lessons learned from a decade of operating this magnet have provided guidance for the development of an advanced TRL-6 magnet.

The TRL-6 magnet uses HTS tape that allows the magnet to operate at temperatures around 60 K, an order of magnitude higher than the 5 K operating temperature of the current LTS magnet. Operating at this elevated temperature reduces the system mass and power consumption by eliminating the need for energy-intensive multistage cryocoolers. The HTS tape is a second generation (2G) rare earth barium copper oxide based wire. This technology has been around since before the development of Ad Astra's LTS magnet system but was not a viable option at the time. The performance of HTS tape has steadily improved over the past decade while the price decreases which makes it undeniably the best choice for a new magnet.

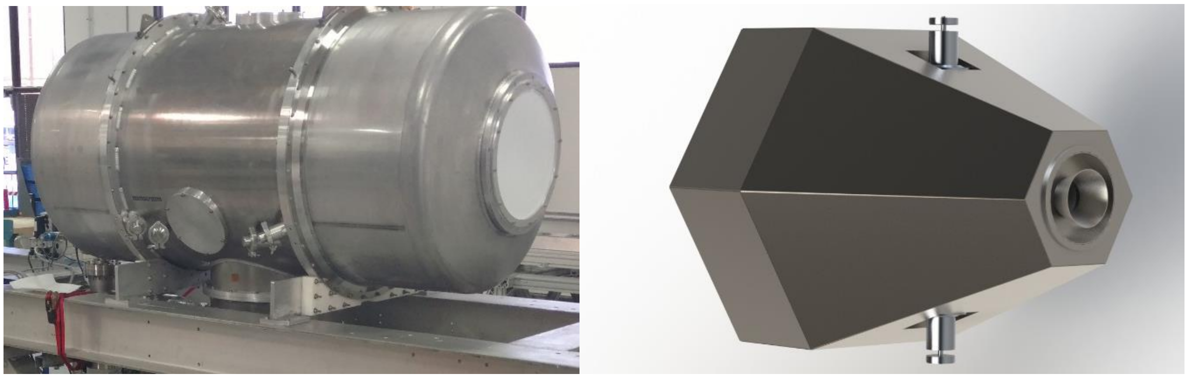

Fig. 2 To scale: (left) LTS magnet used in VX-200SS™ experiment, (right) HTS magnet model

To produce the proper magnetic field shape, the HTS tape is wrapped around two mandrels. The primary mandrel is a small diameter tube with five HTS tape coils that provide the magnetic geometry specifically tailored to the rocket core. The bucking mandrel is a large diameter ring where the bucking coil is mounted. The bucking coil is aligned coaxially with the primary coils and wrapped in the opposite direction relative to the primary coils making the system a magnetic quadrupole that effectively creates a net-zero magnetic torque. Without the bucking coil, the magnet would be a dipole that is more susceptible to the magnetic dipole of Earth, resulting in complications to a spacecraft's guidance, navigation, and control (GN&C). Figure 3 shows a simplified sketch of the coil cross sections where the dotted line is the centerline, the ⊙ represent the magnetic field coming out of the plane of this page (towards you), and the ⊗ represents the magnetic field going into the plane of this page (away from you). The five primary coils are wrapped around the primary mandrel (blue) and the bucking coil is wrapped around the bucking mandrel (red).

In past designs like the VF-200, the net-zero magnetic torque was achieved by having two superconducting magnets (and two thruster cores) with parallel axes and opposite field directions. However, modern HP SEP missions have limited power budgets so a double thruster core system becomes inefficient. The system mass is greatly reduced by cutting the system down to a single thruster core that can use all the power allotted to it. The bucking coil in the TC-1Q™ performs the same function as the second superconducting magnet in the VF-200 allowing for a smaller footprint, lower mass, and an overall more efficient system. As power levels increase due to bigger power systems, better solar panels, and eventually in-space nuclear power sources, TC-1Q™ systems can be clustered or the double thruster core can be reevaluated.

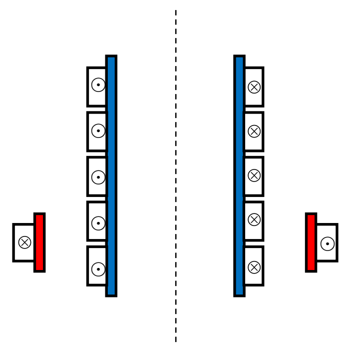

Fig. 3 Simplified magnet sketch of the five primary coils and the one bucking coil.

2. Mandrels

Initial analyses of the mandrels have been performed using aluminum. Aluminum is a lightweight option with high thermal conductivity that efficiently removes heat from the coils of HTS tape. Aluminum is a time-tested, low-risk, low-cost option. However, an alternate mandrel design being considered has a carbon fiber body around which the HTS tape is wrapped and uses thermal shunts to move the heat from the HTS tape. This design decreases the mandrel mass, increases manufacturing cost, and increases risk. Trade studies for the mandrel are ongoing because it may be possible to offset the added manufacturing cost by the cost of reducing mass.

3. Cryostat

The two mandrels are mounted on highly-stiff, thermally-insulated struts inside the cryostat. The cryostat consists of a frame covered with panels and a bore tube running along the axis. There are three primary considerations for design and material selection of the cryostat. First, the cryostat must tolerate vibrations at launch. Second, the cryostat must minimize displacement due to the strain resulting from high magnetostatic forces between the primary and bucking coils. Third, the cryostat must withstand a pressure difference between the vacuum inside and the 1 atm pressure outside for magnet ground testing outside of a vacuum chamber. Two additional requirements, using nonmagnetic materials and allowing easy access into the cryostat for maintenance, were assumed from the start along with the basic premises of minimizing both volume and mass.

Multiple frame geometries that closely encased the magnet coils were analyzed. A tapered hexagon with chicken-foot shaped beams was the best option, winning in many categories such mass reduction and least deformation. This frame is shown in Fig. 4.

The complex geometry due to the beam cross section and O-ring grooves makes manufacturing difficult. It is technically possible to cast the frame but likely prohibitively expensive due to the high setup cost relative to the small batch being ordered (only one or two frames). Processes like extrusion or drawing could produce the beams which could then be welded together. As welding is a certainty with common manufacturing processes, additive manufacturing was investigated as an alternative.

Although additive manufacturing has become trendy in the recent years due to its great potential, preliminary investigations have shown limited usefulness for producing this frame. The primary issues surrounding additive manufacturing for our application is the geometry and size. Sciaky, Inc. sells systems that were producing 35-inch titanium tanks back in 2015 with plans to increase tank size to 48 inches, for example.[1] Unfortunately, that electron beam additive manufacturing (eBAM) process that currently prohibits the printing of overhangs like those in our frame. Other techniques like selective laser sintering (SLS) allow overhangs to be printed but do not have a large enough build volume to produce the frame. Material selection was not a limiting factor. Additive manufacturing processes already produce parts made of aluminum, stainless steel, titanium, and many other metals.

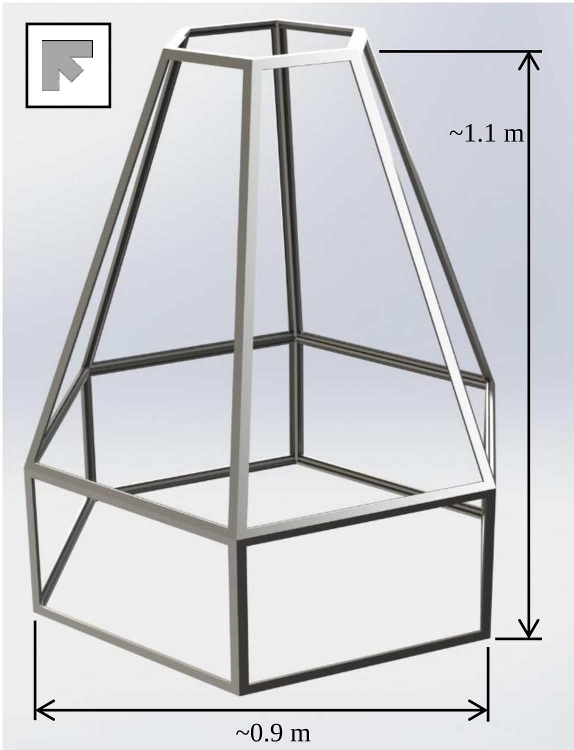

Fig 4. Cryostat frame with dimensions and beam cross section inset

4. Cryocoolers

Heat is pulled from the HTS tape through the mandrel by cryocoolers. The elevated operating temperature of the HTS tape compared to the operating temperature of the LTS tape greatly increases the number of cryocooler options available for our application. Of particular note is Sunpower, Inc., a company that sells Stirling cycle cryocoolers such as the CryoTel® GT that are highly efficient, low-vibration, and space-rated. Thermal analyses show that two CryoTel® GT cryocoolers effectively cool the mandrels to temperatures below the operating temperature of the HTS tape and maintain that temperature when the waste heat generated by the coils is introduced. Both two-stage cryocoolers currently in operation on the LTS system weigh nearly 20 kg each whereas the mass of a CryoTel® GT unit is 3.1 kg.

B. RF PPUs

The RF PPUs used in the VX-200SS™ experiment are located outside the main vacuum chamber as they are not vacuum compatible. The current ICH RF PPU is shown on the left in Fig. 5. It is a large unit roughly 1.5 m tall that is cooled by both convection and conduction. We have been closely working with Aethera Technologies LTD who designed the TRL-5 ICH RF PPU shown on the right in Fig. 5. The TRL-5 ICH RF PPU is vacuum compatible, conduction cooled, and magnetically shielded all while drastically reducing the volume and mass. This design can be scaled to process more or less power depending on the desired TC-1Q™ power level.

Vacuum compatibility is a requirement for TRL-5 due to the environment in which the system will operate. For TC-1Q™ as a system to reach TRL-6, each subsystem must be vacuum compatible so the system as a whole can be tested in vacuum. Conduction cooling is critical as the vacuum environment eliminates convection cooling and the system runs at too low a temperature for radiation to successfully transport the heat. The conduction cooling is achieved by a simple fluid loop operating in the same low temperature range as the other cooling loops excluding the rocket core. Magnetic shielding is necessary due to the close proximity of the PPUs to the strong magnetic fields near the core. The effect of the strong magnetic field on the sensitive components inside the PPU is mitigated both by the design of the enclosing shield and the orientation of the PPU relative to the magnetic field lines.

Most apparent in Fig. 5 is the volume difference. The current ICH RF PPU has a volume of roughly 0.6 m^3. The TRL-5 ICH RF PPU design has a volume of nearly 0.06 m^3. Although its volume is an order of magnitude lower than its predecessor, the TRL-5 ICH RF PPU is much more dense and has a mass of nearly 50 kg. This mass is still much lower than it had been previously expected, with calculations showing that a version of the VX-200SS™ ICH RF PPU scaled to TRL-5 would have a mass of 82.5 kg. [2]

Fig. 5 To scale: (left) ICH RF PPU currently in use, (right) design of TRL-5 ICH RF PPU.

V.   Conclusion

This paper discusses how the parallel development of technologies in other industries stimulates innovation in the systems surrounding VASIMR®, particularly its magnet and RF PPUs. HTS tape loosens system requirements allowing for mass savings derived from a simplified mandrel design and lightweight cryocoolers. The mandrel can potentially be even lighter with the use of carbon fiber. Additive manufacturing cannot be used to produce the magnet frame but those processes are constantly being improved and refined so potential future use has not been ruled out. The RF PPUs are a major step forward through TRL-5. These PPUs will be able to operate inside a vacuum environment near a high magnetic field thanks to conduction cooling and magnetic shielding. The new technologies in both the HTS magnet and the RF PPUs lower the system mass ultimately allowing for more payload on future missions.

Acknowledgements

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