Submitted to: International Conference on Electromagnetics in Advanced Applications, Torino, Italy. Sept 13 to 17, 1999. Manuscript completed July 1999. NASA, Johnson Space Center, Houston, TX 77058, USA.

The Development of the VASIMR Engine

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Abstract--- **The Variable Specific Impulse Magnetoplasma Rocket (VASIMR) is an open-ended, RF-heated, magnetic mirror-like plasma device. The three-stage system features an RF driven plasma generator/injector, an RF power booster and a hybrid magnetic nozzle. Its electrodeless design enables high power density. The system provides access to very high and variable thrust and exhaust velocities ($3x10^4$ – $3x10^5$ m/sec) of interest in fast human and robotic interplanetary propulsion as well as efficient, high-payload orbit transfer capability. In its near-term form, the VASIMR is an electrically driven rocket, powered by solar or nuclear energy. However, its technology also paves the way for ignited plasma rockets powered by controlled thermonuclear fusion. The development of the VASIMR began at the NASA Johnson Space Center (JSC) in 1980 and has continued since. At present, a JSC-led, multi-center theoretical, experimental and systems engineering program is under way. This paper describes the development of the VASIMR from its early stages to the present, focusing on the main physics and engineering areas of interest. The latest theoretical and experimental results, mission applications, systems engineering, as well as the first space experiment being planned for this technology are discussed in detail.**

I. INTRODUCTION

The development of advanced propulsion technologies represents a cornerstone in the successful realization of long-term space travel. To be sure, present chemical propulsion is one of the fundamental limitations in robotic exploration of the outer Solar System and certainly of inter-stellar space. For human space exploration, the limitations are even more daunting. Unlike their robotic precursors, human interplanetary spacecraft must possess some key features, which are essential for the preservation of human life. These vehicles must be fast, reliable, "power rich," and be capable of reasonable abort options for crew survival in the event of unexpected malfunctions.

Future propulsion systems must also be capable of handling, not just the "cruise" phase of the journey, but also provide sufficient "maneuvering authority" near the origin and destination planets. Thus, these engines should provide a constant power throttling capability similar to the function of the transmission in an automobile or the feathering of a propeller engine.

Several new and promising concepts are being investigated in order to address these issues. Many explore the intrinsic gains in performance afforded by plasma based systems over their chemical counterparts. Advanced concepts such as VASIMR, the Hall Effect thruster, the Lorentz Force Accelerator and others are in various stages of development and field test and offer great promise for the future of space exploration.

II. CONCEPT DESCRIPTION

The VASIMR engine, shown schematically in fig. 1., is a high power, electrothermal plasma rocket, capable of exhaust modulation at constant power. It consists of three major magnetic cells: “forward,” “central,” and “aft,” where plasma (typically hydrogen) is respectively injected, heated and expanded in a magnetic nozzle. This magnetic configuration is called an asymmetric mirror. The forward cell handles the main injection of propellant gas and the ionization subsystem. The central cell acts as an amplifier to further heat the plasma to the desired magnetic nozzle input conditions. The aft cell is a hybrid two-stage magnetic nozzle, which converts the thermal energy of the fluid into directed flow, while protecting the nozzle walls and insuring efficient plasma detachment from the magnetic field.

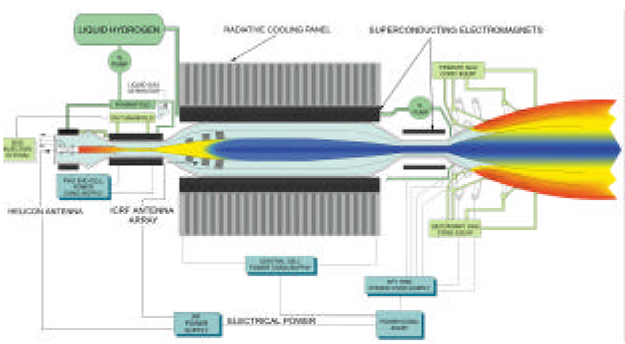

Fig. 1. Schematic of the VASIMR system

In its present design, the plasma in the VASIMR is created by a helicon injector and heated by the process of ion cyclotron resonance (ICR). Both techniques utilize radio frequency (RF) electromagnetic waves to accomplish their goal. The partition of the total RF power into plasma production (helicon) and plasma heating (ICR) is dependent on the desired operational regime. Thus the VASIMR lends itself to exhaust variability through power management to both of these systems. For example, if high thrust is desired, RF power is predominantly fed to the helicon injector, with an appropriate reduction in ICR heating. If high specific impulse is required, RF power is predominantly diverted to the ICR system with concomitant reductions in thrust. The total RF power remains constant. This general approach to exhaust modulation in the VASIMR is called constant power throttling (CPT.)

Other techniques for exhaust modulation are also being considered. For example, the degree of plasma “choking” produced by the exhaust cell magnetic mirror could be used to keep some of the plasma longer in the ICR heating volume and increase its temperature (and hence I_{sp}.) On the other hand, the addition of hypersonic neutral gas at the magnetic expander could produce a plasma afterburner effect with considerable increase in the thrust.

Operationally, exhaust modulation can have profound implications to rocket propulsion. For example, the high thrust mode of the VASIMR can be employed in the early stages of orbital boost in a high gravity environment. As the vehicle escapes the gravitational pull, its exhaust would gradually transition to a high I_{sp} mode, and continue to accelerate the craft to its full cruise speed. The process would reverse itself as the ship approaches the high gravity environment of its destination. For planetary fly-by, or deep space missions not requiring orbital insertion, the spacecraft engine would be capable of better matching of the exhaust velocity to the vehicle velocity for optimum propulsive efficiency. Other benefits pertaining to orbital operations and spacecraft attitude control are also envisioned. All of these features are currently under investigation.

Other important system characteristics involve an electrodeless design in a multi-stage architecture, which optimizes overall system function, a hybrid magnetic nozzle with a “plasma afterburner” provides high thrust capability when operational needs so dictate.

Finally, while the present VASIMR system is driven by an external power source, it can serve as a precursor to an eventual fusion rocket, as described by several authors [1], [2], in an evolutionary process and paving the way for much of the technology. Such development will revolutionize space travel, as we know it today.

III. EXPERIMENTAL STUDIES

The VASIMR system has been under development since the early eighties [3], [4]. Experimental, theoretical and system engineering studies have been under way for several years [5]. In 1995, an experimental facility to test the basic physics principles of the VASIMR was established at the NASA Lyndon B. Johnson Space Center in Houston Texas. Fig. 2 shows a synoptic view of the experiment in its early high-power configuration. The early system was designed to explore a full tandem magnetic mirror concept with a high plasma volume, high magnetic field (3 Tesla at the mirrors) and integrated heating and fueling in the same magnetic cavity.

A more recent experimental configuration is shown in Figs. 3 and 6. These have been chosen to test simpler magnetic arrangements, which could be flight, tested early in the next decade.

Experimental data measured from the early plasma discharges with helium are shown in fig. 4. The data are plotted for two magnetic field intensities, showing expected plasma density enhancement with magnetic field. The electron temperature profile is nearly flat at 5-6 eV. The temperature data shows the defining presence of a 5-cm diameter quartz tube limiting the plasma size at the source. The discharges are in full steady state mode.

Fig. 2. Dec. 1997 photograph of the VASIMR experimental facility at the NASA Johnson Space Center

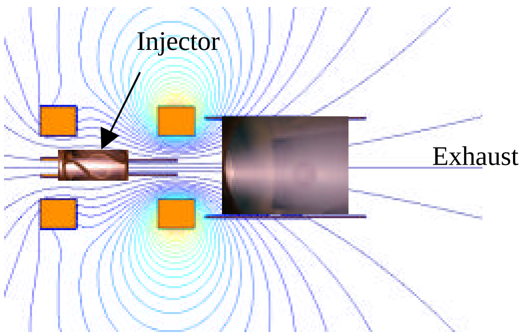

Fig. 3. Two magnet configuration showing magnetic field structure and actual plasma flow

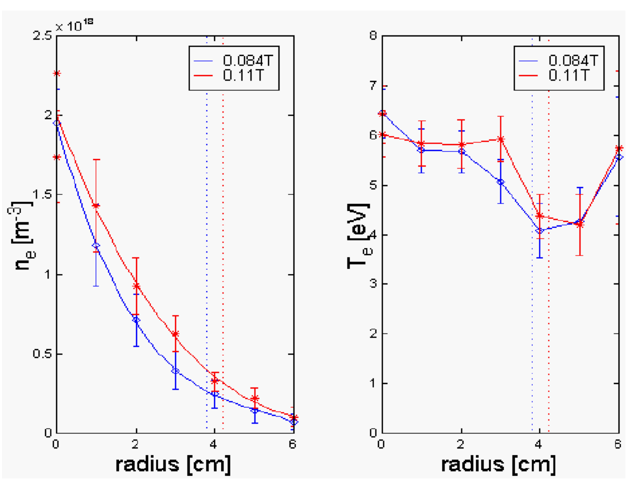

Fig. 4. Helium plasma density and temperature data at 1kW obtained at the ASPL test site.

More recently, ASPL experiments and those at a sister device at the Oak Ridge National Laboratory (ORNL) have switched to pure H_2, as well as gas mixtures of He and H_2. Preliminary results with H_2 are shown in fig.5. These were obtained with the ORNL device at a frequency of 21 MHz and power levels of 1.3 kW. While these data already show a high-density capability. Optimization studies at both facilities are presently under way to further explore the operational envelope.

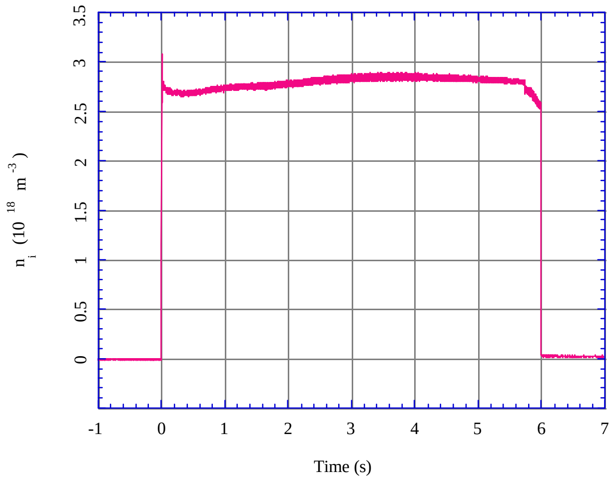

Fig. 5. Hydrogen plasma density data for a helicon injector output at 1.3kW obtained at the ORNL test site.

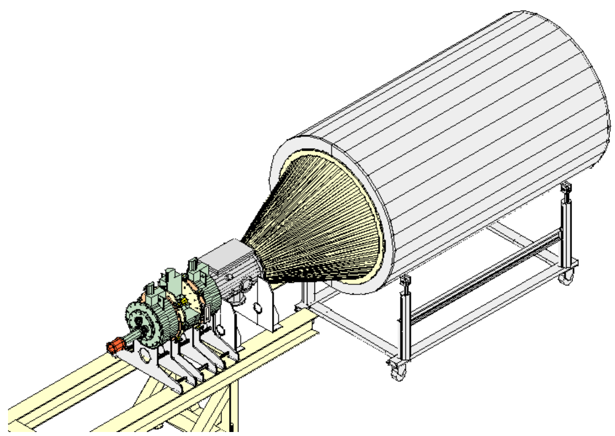

Fig. 6. Present ASPL 3-magnet configuration designed for more uniform field experiments on hydrogen and gas mixtures.

IV. Theoretical Studies

Along with the experimental investigations, the ASPL conducts a parallel effort in plasma theory and simulations. These studies generate physics modules for integration into computer simulations. For example, Fig. 7 shows the trajectories of single ions in the central and aft cells. The axial and parallel (to the field) velocities of these particles are followed and plotted as functions of axial position. The lower plot shows the axial velocity boost given to the ions by the diverging magnetic field.

In a similar fashion, the computer simulation shows ion cyclotron power deposition. The energy is imparted to the perpendicular motion of the ions and subsequently transferred to axial motion by the process of adiabatic expansion in the magnetic nozzle. The various energy components are plotted versus axial position in fig. 8.

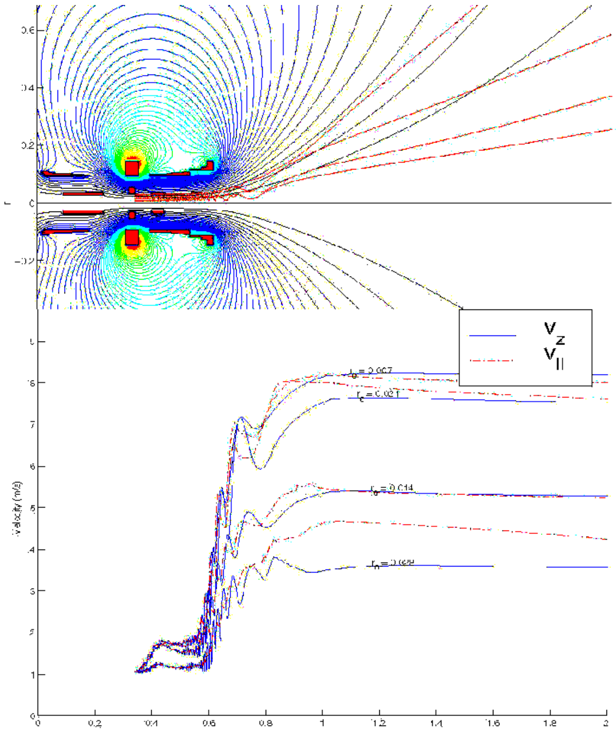

Fig. 7. ICR-heated ions at various radial positions in the VASIMR are accelerated in the magnetic nozzle.

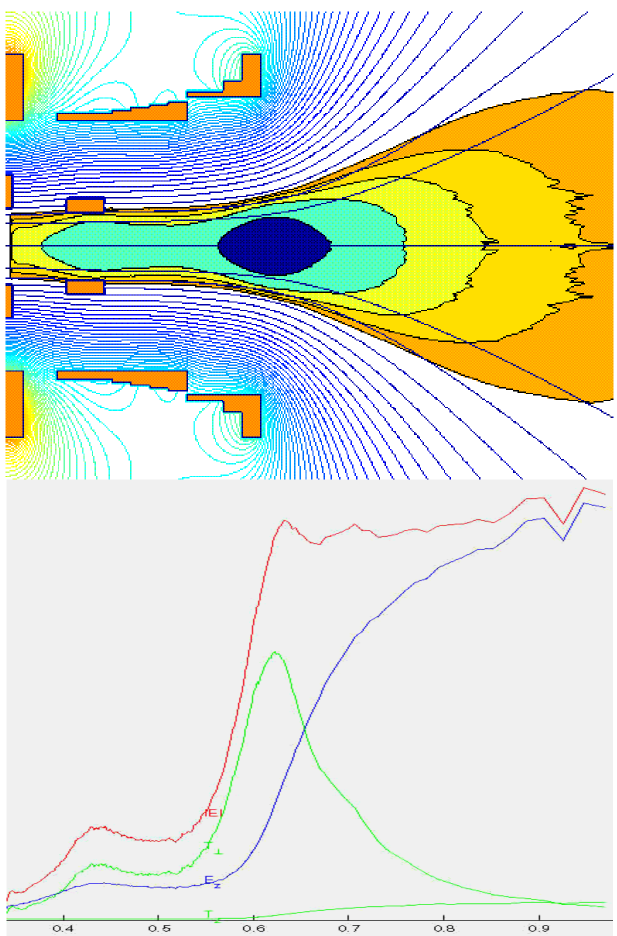

Fig. 8. VASIMR ICR power deposition contours (top) and plasma total, parallel and perpendicular energy.

V. ENGINEERING AND TECHNOLOGY DEVELOPMENT

Important engineering aspects are being considered in concert with the development of the physics. For example, the utilization of cryogenic propellants such as hydrogen and helium will lend itself to regenerative thermal designs. Advanced heat pipes, high temperature superconductors and new solid state RF amplifiers are some of the new technologies which play an important role in the development of the VASIMR. These are being explored experimentally in the laboratory and in a proposed robotic flight experiment, called the Radiation and Technology Demonstrator (RTD) mission. This mission is currently under development for space deployment from the shuttle orbiter in early 2003.

In the RTD mission, the VASIMR will operate together (but not simultaneously) with an advanced 10kW Hall thruster to provide primary spacecraft propulsion. Both thrusters will draw electrical power from a solar array and demonstrate advanced but distinct propulsion technologies in a single bus. As a secondary objective, the RTD also seeks to deploy an array of microsatellites, at 4000 km intervals, as it spirals out to about 3 Earth radii. The microsatellites will provide in-situ radiation data on the Van Allen radiation belts. A simplified schematic of the RTD spacecraft is shown in fig. 9.

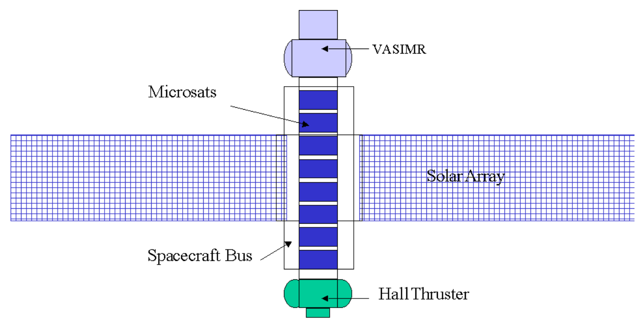

Fig. 9. The RTD spacecraft is a 10 kW solar-powered demonstrator, which will test advanced propulsion technologies such as the VASIMR and the Hall Thruster.

The technology development effort proceeds on several fronts. For example, the generation of efficient plasma heating must not preclude a compact and lightweight design. Moreover, the production of strong magnetic fields in space requires advanced, high temperature superconductors. These must take advantage of the unique thermal properties of space. A preliminary conceptual design for a high temperature .7 Tesla superconducting magnet has been completed. This monolithic magnet utilizes new BSCCO (Bismuth, Strontium, Calcium, Copper, Oxide) superconducting tape. The present design, shown in fig. 10 weighs about 20 kg and operates at 35^{o} K [7].

Light weight and compact RF power conversion is also a key aspect of VASIMR development. New advances in high-power solid-state RF power amplifiers have been achieved by our group, and are currently undergoing testing at the ASPL and the Oak Ridge facility. The new amplifiers enable space-relevant application in the 1-50 MHz range at about 10 kW. An advanced version of this design will be incorporated in the RTD mission [8].

The RTD VASIMR engine will operate with hydrogen propellant at a constant specific impulse of 10,000 sec. The power level of 10kW will produce a thrust of approximately .1 N at an efficiency of 50%. The main goal of this test is a "proof of concept", which will pave the way for more ambitious space experiments designed to characterize the VASIMR over its entire operational envelope. A simplified trimetric view of the RTD VASIMR engine is shown in fig. 11.

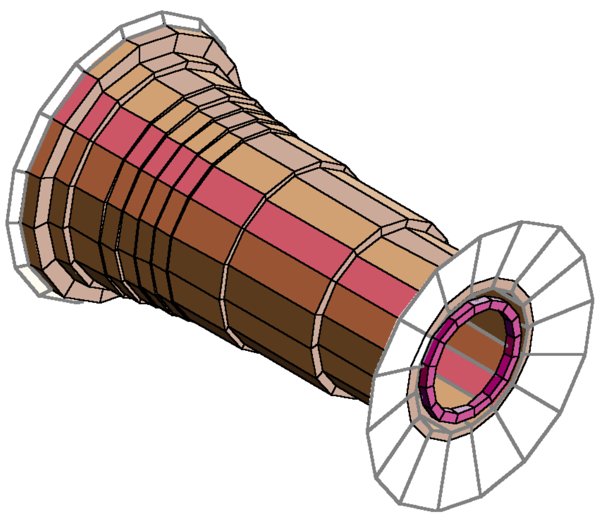

Fig. 10. Conceptual VASIMR superconducting magnet for the RTD mission.

Other flight experiments are envisioned to demonstrate various aspects of the technology in a gradual but brisk technology development effort. Ground laboratory development will lead the space testing, but rapid verification of the laboratory results in a flight environment could be facilitated by the International Space Station. Moreover, propulsion technology development on the ISS could also incur in operational cost savings in conventional chemical propellant for boosting the orbit of the station. For example, long duration plasma burns on board the ISS could have desirable and appreciable effects on the ISS from the point of view of orbit decay reduction and microgravity.

VI. Concluding Remarks

The development of VASIMR technology addresses some critical areas in long-range human and robotic space exploration of the solar system and beyond.

For robotic spacecraft, the high power and specific impulse achievable enable a class of missions well beyond anything possible with current technology. These would advance the goals of the NASA Origins Enterprise. Closer to Earth, the VASIMR could also have a strong impact on commercial and space research operations by enabling missions with spacecraft which could have both maneuvering authority, as well as propulsive efficiency. Such craft would provide efficient round-trip capability to the high-energy orbits of commercial interest in the Earth-Moon environment, enabling rapid and economical satellite maintenance, repair and refueling.

For human exploration, VASIMR technology enables very fast human planetary transits (<100 days to Mars [9]) which also preserve a high payload mass fraction. The reduction in trip time couples into a reduction in the human physiological de-conditioning caused by long exposure to microgravity. Moreover, the utilization of hydrogen propellant as an effective shield will also significantly reduce the radiation dose astronauts will receive. In addition, the technology enables a "power rich" mission architecture with abort capability essential for human survival in the event of unforeseen contingencies.

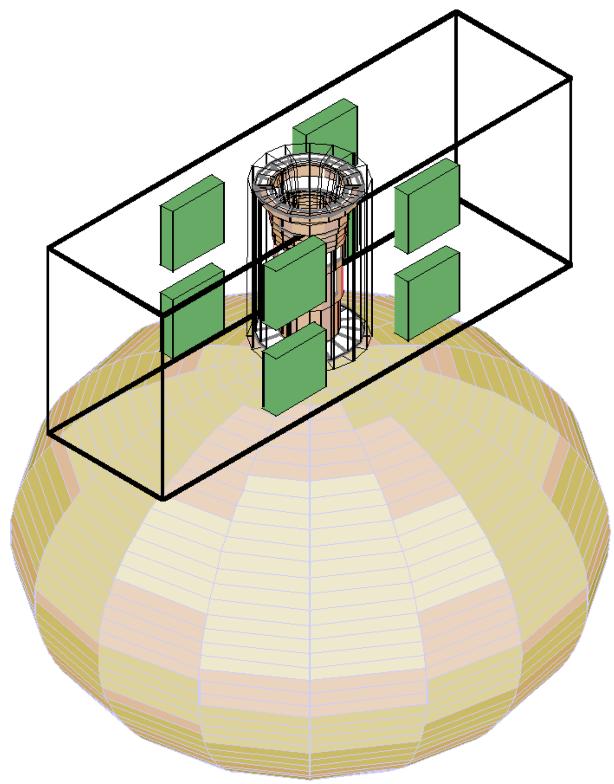

Fig. 11. Simplified schematic of RTD VASIMR engine.

Finally, the VASIMR is a precursor to fusion rockets, where the high power generated by the thermonuclear reaction in the plasma will enable even faster trips with the added benefit of an artificial gravity caused by the continuous thrust of the engine. While fusion rockets remain a distant dream, the possibilities are truly awesome and it is not too early to begin preparing our young for the wonders that are yet to come.

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