NASA/TM—2005-213888 AIAA–2005–4227

Overview of Advanced Electromagnetic Propulsion Development at NASA Glenn Research Center

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September 2005

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Prepared for the
41st Joint Propulsion Conference and Exhibit
cosponsored by the AIAA, ASME, SAE, and ASEE
Tucson, Arizona, July 10–13, 2005

National Aeronautics and
Space Administration

Glenn Research Center

September 2005

Acknowledgments

The authors would like to express their gratitude for the support of the Energetics Heritage project managed by Randall Speth and David Hoffman. The authors would like to express their gratitude for the high dedication and workmanship of Glenn technicians in supporting this work, especially Dennis Rogers, James Coy, Donna Neville, and Valarie Roundtree.

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Abstract

NASA Glenn Research Center's Very High Power Electric Propulsion task is sponsored by the Energetics Heritage Project. Electric propulsion technologies currently being investigated under this program include pulsed electromagnetic plasma thrusters, magnetoplasmadynamic thrusters, helicon plasma sources as well as the systems models for high power electromagnetic propulsion devices. An investigation and evaluation of pulsed electromagnetic plasma thruster performance at energy levels up to 700 Joules is underway. On-going magnetoplasmadynamic thruster experiments will investigate applied-field performance characteristics of gas-fed MPDs. Plasma characterization of helicon plasma sources will provide additional insights into the operation of this novel propulsion concept. Systems models have been developed for high power electromagnetic propulsion concepts, such as pulsed inductive thrusters and magnetoplasmadynamic thrusters to enable an evaluation of mission-optimized designs.

I. Introduction

The National Aeronautics and Space Administration (NASA) Glenn Research Center's Very High Power Electric Propulsion task is currently supported by the Energetics Heritage Project. The Energetics Heritage Project is formerly an element of the Aerospace Technology Enterprise's (Code R) Mission and Science Measurement Technology theme, which was transitioned to the Human & Robotics Technology theme in the Office of Exploration prior to being transferred to the Exploration Systems Research & Technology theme in the newly formed Exploration Systems Mission Directorate. The Energetics Heritage Project addresses technology development through an improved understanding of the fundamental physics and the identification and resolution of design challenges to advance the technology. Current activities under this task include the development of high performance pulsed electromagnetic plasma thrusters, gas-fed magnetoplasmadynamic (MPD) thrusters, helicon plasma sources, and systems models for advanced electromagnetic propulsion thrusters. Given that funding for the Energetics Heritage Project ends after Fiscal Year 2005, this paper will provide the status of the activities remaining in that effort.

II. Pulsed Electromagnetic Plasma Thruster Development

Two longstanding goals in electric propulsion are to reduce total system mass and to increase performance capabilities of the system. One approach for achieving either goal is to investigate performance improvements to thruster efficiency. Improvements to thrust efficiency can be utilized to reduce total system mass through the reduction in propellant mass, assuming the reductions in propellant savings are greater than the system dry mass penalties. In power-limited satellites, improvements in thruster efficiency can enhance propulsion capabilities by increasing available thrust to either decrease orbit transfer trip times or to improve drag make-up capabilities of a satellite (Ref. 1).

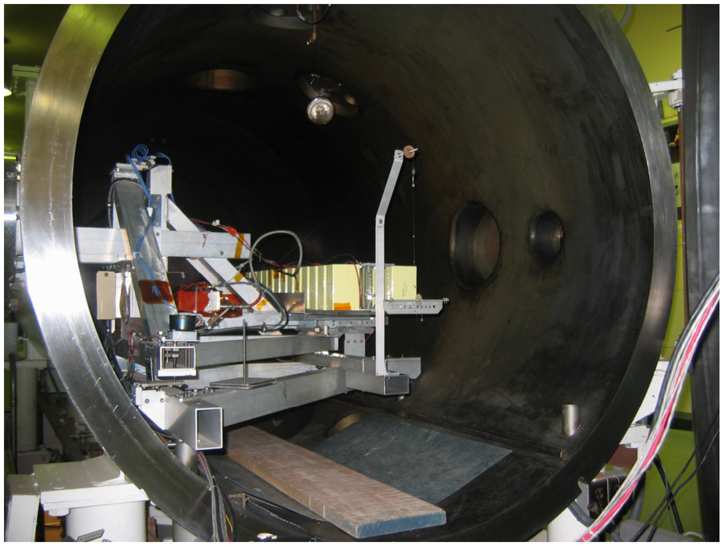

Figure 1.—Laboratory thruster mounted on PPT thrust stand in VF3 at NASA GRC.

Improvements to the operational boundaries of the pulsed electromagnetic plasma thruster performance map have been investigated through a number of approaches under the Energetics program. Performance evaluation of additives to polytetrafluoroethylene (PTFE) has shown that small amounts of carbon added to PTFE significantly reduced propellant ablation rates, while marginally changing thrust. The improvements over nominal PTFE depended on several factors including discharge energy (Ref. 2), electrode geometry (Ref. 3), and propellant composition (Ref. 4). In addition increasing discharge energy with any propellant has been shown to improve thrust efficiency (Refs. 5 to 8). Recently Kamhawi, *et al*. (Ref. 9) have investigated thruster operation at higher discharge energies with two thruster configurations. The first thruster configuration (Fig. 1) was operated with three capacitor arrangements to provide a total discharge capacitance of 100 μF, 180 μF, and 260 μF. This thruster configuration was operated over a range of discharge energies from 50 to 700 J with thrust efficiencies ranging from 4 to 35 percent as shown in Figure 2. The second thruster configuration was operated with a total discharge capacitance of 260 μF. This thruster configuration was operated over a range of discharge energies from 300 to 700 J with thrust efficiencies ranging from 23 to 37 percent. Discharge current waveforms were collected and compared to predictions from a pulse forming network circuit model. Future work will evaluate various electrode and propellant configurations (Ref. 10).

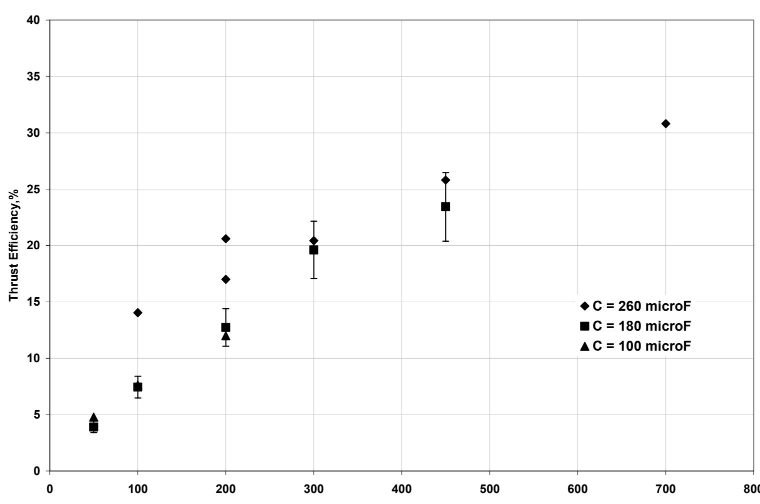

Figure 2.—Configuration thrust efficiency magnitudes for discharge energy levels between 50 and 700 J.

III. High Power Magnetoplasmadynamic Thruster Development

High power magnetoplasmadynamic thrusters are being developed as a propulsion system for cargo transport and possibly piloted human to Mars bases and the outer planets and robotic deep space exploration missions. Electromagnetic thrusters in the laboratory have demonstrated the ability to produce significantly higher thrust densities than electrostatic electric propulsion systems. The ability to generate high thrust densities results in decreased system complexity through reductions in the number of thrusters required to perform a given mission. NASA GRC is developing and testing quasi-steady MW-class thrusters as a prelude to steady-state high power thruster tests. Quasi-steady testing will focus on improving performance, specifically thrust efficiency. Previous work on the high power pulsed thruster test facility and preliminary performance data for a quasi-steady baseline MPD thruster geometry were presented (Ref. 11) and are shown in Figure 3.

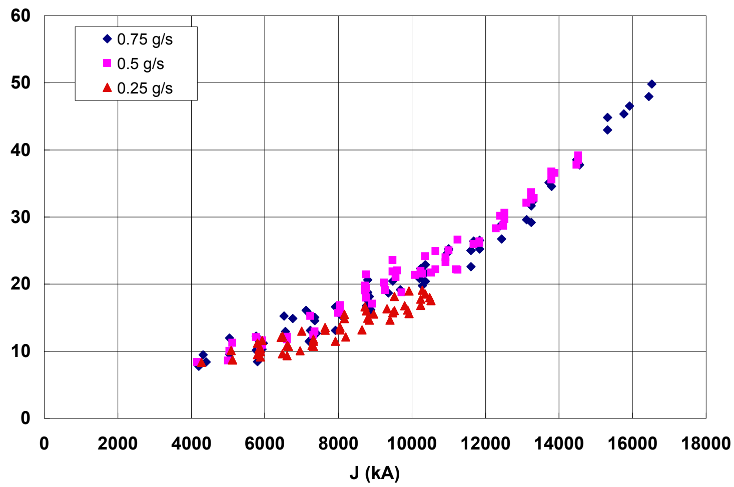

Figure 3.—Self-field MPD thruster quasi-steady performance data with argon.

Future work will focus on applied-field performance characterization of the baseline thruster geometry (Ref. 12) as shown in Figure 4 as well as an interrogation of the thruster plasma flowfield with an array of intrusive and non-intrusive diagnostics. The extension of the work to applied-field thrusters requires only minor modifications to the thrust stand to eliminate applied-field tare effects. Modifications underway include incorporating features found on the NASA GRC pulsed plasma thruster thrust stand such as a magnetic damper and linear variable displacement transducer system. The damping system is required to cancel magnet-induced oscillations prior to the discharge. The intent of the quasi-steady tests is to improve the understanding of MPD behavior. Insights gained from this work are anticipated to be applicable to the MPD thruster field in general, independent of propellant.

Figure 4.—Baseline applied-field MPD thruster installed on pulsed thrust stand.

IV. Helicon Plasma Source Development

Helicon plasma sources offer several unique features such as high-density plasmas (10^{19} m^{-3}) at relatively low powers (100's of watts) as compared to other electric propulsion thrusters as well as the promise of electrode-less electric propulsion. The main benefit of electrode-less electric propulsion is the potential mitigation of electrode erosion through the elimination of thruster electrodes from high-energy plasma environment in electric propulsion thruster discharge chambers. Low-power, high-density plasma sources offer the potential to decrease thruster size at a given power level. However, thruster scale helicon sources represent a departure from the larger laboratory devices currently under investigation.

Potential applications include incorporating helicon plasma sources into the discharge chamber of traditional devices such as hall or ion thrusters (Ref. 13), using the helicon waves to heat and accelerate plasmas through a proposed double layer effect (Ref. 14), or operating with propellants derived from extraterrestrial resources (Refs. 15 and 16). Initial focus was on the investigation of a 13.56 MHz, 300 W helicon plasma source, which has demonstrated plasma generation (Fig. 5) but poor coupling. However, related dispersion calculations indicated that higher frequencies might allow better coupling (Ref. 17). As a result the experiment has been upgraded to include a tunable 10-100 MHz, 300 W microwave power supply and an extended magnetic coil.

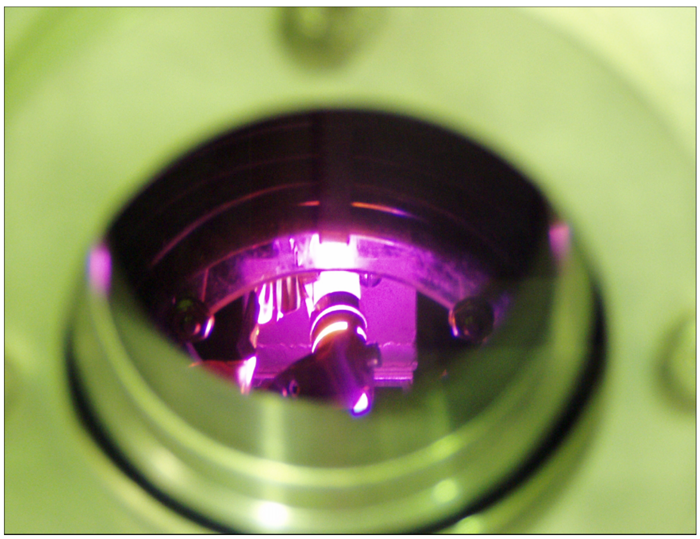

Figure 5.—300 W helicon plasma source operating at 13.5 MHz in vacuum.

V. Mission and Systems Models for Advanced Electromagnetic Thrusters

An on-going activity at NASA GRC is the development of thruster models, which can be used to optimize thruster designs based on specific exploration mission objectives. These models are designed to be incorporated in mission trajectory optimization codes as needed in application to Exploration and Science mission analysis (Ref. 18). The performance models are based on input of specific impulse and power, and yield efficiency and thruster operating parameters. The concepts of interest include self-field and applied-field magnetoplasmadynamic thrusters, pulsed inductive thrusters, and helicon/electron cyclotron resonance thrusters. Self-field and applied-field MPD thruster models have been developed for use in mission studies and provide estimates for performance and mass (Refs. 18 and 19). An initial physics-based performance model has also been derived for the pulsed inductive thruster (Ref. 20) and has been incorporated into a preliminary set of scaling relations (Ref. 21) as shown in Figure 6. Similarly, a preliminary zeroth order model for helicon/electron cyclotron resonance thruster concepts has been developed (Ref. 15). While the ideal propulsion performance of radiofrequency (rf) concepts has been modeled in terms of fundamentals, several unknowns at both the physics and engineering levels remain. For example, the physics of plasma expansion and detachment in a magnetic field remain as outstanding questions in terms of feasibility and efficiency, which will strongly affect performance. The design, power efficiency, lifetime, and mass of 10 to 1000 kW, space rated rf power systems is an engineering unknown with little specific design work to date. These fundamental and systems-level issues are still being investigated experimentally and analytically.

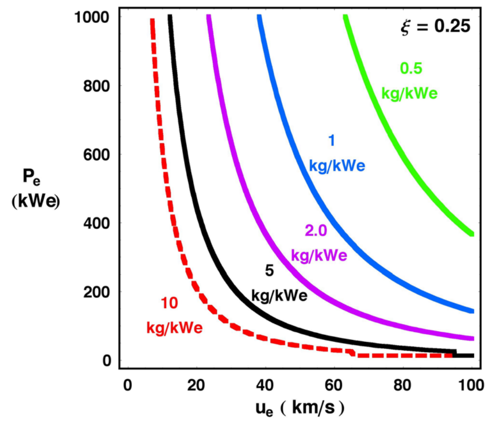

Figure 6.—PIT scaling relationships for high power applications.

VI. Conclusion

Electric propulsion technologies currently being investigated under the Energetics project include pulsed electromagnetic plasma thrusters, magnetoplasmadynamic thrusters, helicon plasma sources as well as the systems models for high power electromagnetic propulsion devices. An investigation and evaluation of pulsed electromagnetic plasma thruster performance at energy levels up to 700 Joules is underway and has demonstrated efficiencies up to 37 percent. On-going magnetoplasmadynamic thruster experiments will investigate applied-field performance characteristics of gas-fed MPDs for comparison to self-field performance data. Plasma characterization of helicon plasma sources will provide additional insights into the operation of this novel propulsion concept and its effective application in electric propulsion systems. Systems models have been developed for high power electromagnetic propulsion concepts, such as pulsed inductive thrusters and magnetoplasmadynamic thrusters to enable an evaluation of optimized designs for exploration and science mission objectives.

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave blank*)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	September 2005	Technical Memorandum

4. TITLE AND SUBTITLE

Overview of Advanced Electromagnetic Propulsion Development at NASA Glenn Research Center

5. FUNDING NUMBERS

WBS–22–612–50–81–14

6. AUTHOR(S)

Eric J. Pencil, Hani Kamhawi, James H. Gilland, and Lynn A. Arrington

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
John H. Glenn Research Center at Lewis Field
Cleveland, Ohio 44135–3191

8. PERFORMING ORGANIZATION REPORT NUMBER

E–15259

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Washington, DC 20546–0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

NASA TM—2005–213888
AIAA–2005–4227

11. SUPPLEMENTARY NOTES

Prepared for the 41st Joint Propulsion Conference and Exhibit cosponsored by the AIAA, ASME, SAE, and ASEE, Tucson, Arizona, July 10–13, 2005. Eric J. Pencil and Hani Kamhawi, NASA Glenn Research Center; James H. Gilland, Ohio Aerospace Institute, 22800 Cedar Point Road, Brook Park, Ohio 44142; and Lynn A. Arrington, QSS Group, Inc., 21000 Brookpark Road, Cleveland, Ohio 44135. Responsible person, Eric J. Pencil, organization code RPP, 216–977–7463.

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Subject Category: 20

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13. ABSTRACT ***(Maximum 200 words)***

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14. SUBJECT TERMS

Electric propulsion; Magnetoplasmadynamic thrusters; Pulsed plasma thrusters; Helicon thrusters

15. NUMBER OF PAGES

12

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102