CHARACTERIZATION OF PLASMA DISCHARGES IN A HIGH-FIELD MAGNETIC TANDEM MIRROR

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ABSTRACT

High density magnetized plasma discharges in open-ended geometries, like Tandem Mirrors, have a variety of space applications. Chief among them is the production of variable Specific Impulse (I_{sp}) and variable thrust in a magnetic nozzle. Our research group is pursuing the experimental characterization of such discharges in our high-field facility located at the Advanced Space Propulsion Laboratory (ASPL). These studies focus on identifying plasma stability criteria as functions of density, temperature and magnetic field strength. Plasma heating is accomplished by both Electron and Ion Cyclotron Resonance (ECR and ICR) at frequencies of 2-3 Ghz and 1-30 Mhz respectively, for both Hydrogen and Helium. Electron density and temperature has measured by movable Langmuir probes. Macroscopic plasma stability is being investigated in ongoing research.

INTRODUCTION

One of the most important issues being addressed today in connection with human interplanetary travel is the crew's prolonged exposure to weightlessness as well as the high radiation dosage which accrues during these long voyages. From this point of view, it becomes crucial to achieve a minimum trip-time as well as to extend the ship's acceleration schedule consistently with human and power plant limitations.

However, flexibility in these well-known "trajectory variables" remains limited by the capabilities of conventional (constant I_{sp}) chemical engines. Trip-times remain "high" and severely restricted by payload and fuel constraints while the acceleration time is negligibly short compared to the total trip.

Intensive research in the development of higher power and I_{sp} electric and thermal rockets (including Nuclear) has ameliorated the payload to fuel limitation while somewhat reducing the trip-time. However, it has been well known[1] that the attainment of high specific impulse is not always the best approach to rocket propulsion. In all realistic cases, the high I_{sp} comes only at the expense of thrust. While the fuel requirement to achieve the trip may be drastically reduced over a low I_{sp} case, the trip-time rapidly increases. Actually, the best compromise of thrust and specific impulse is one where the two quantities are allowed to vary continuously depending on the conditions of flight.

Optimum I_{sp} variations can be very high (tens of thousands of seconds,) depending on the particular mission. If these conditions are achieved, trip-times of the order of 3-4 months can be achieved for missions to Mars. Moreover, the optimization of the acceleration profile leads to gains in payload fraction over the conventional chemical or nuclear thermal rocket.

These, hitherto unattainable, rocket qualities are now becoming possible with the advent of new technologies in plasma heating and containment which were developed for the Controlled Thermonuclear Research Program. Additionally, recent developments in high temperature superconductivity have pushed these embryonic concepts even further into the realm of engineering design and field test.

The author has been engaged over the past decade in the development of a variable thrust/I_{sp}, RF-heated electrothermal rocket[2,3,4,5] based on the technology of Tandem Mirrors developed for the

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1 J. H. Irving and E. K Blum
Comparative Performance of Ballistic and Low-thrust Vehicles for Flight to Mars. Vistas in Astronautics; Editors: Morton Alperin and Hollingsworth F. Gregory. Vol. II, Pergamon Press, 1959

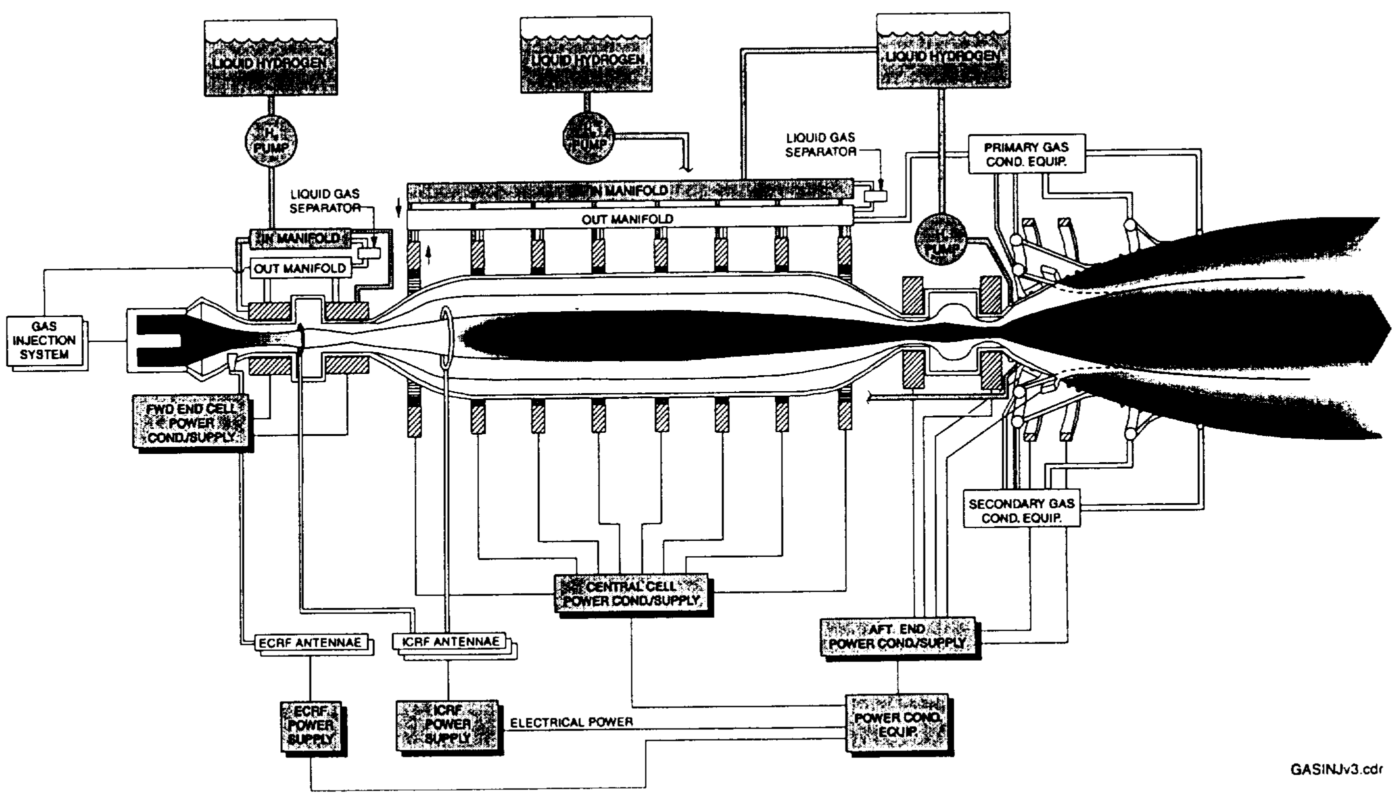
2 F. Chang Díaz, T. F. Yang and W. A Krueger; Numerical Modeling of the Hybrid Plume Plasma Rocket. AIAA Intl. Electric Propulsion Conf. Alexandria, Va. June 1986.

3 F. R. Chang Díaz, et. al.; A Tandem Mirror Hybrid Plume Plasma Propulsion Facility; AIAA/ IEPC 88-126, Oct. 1988.

thermonuclear fusion program. A schematic of the concept is shown in Fig.1. The particular approach considered here, not being a fusion concept itself, has permitted a substantial relaxation in the physics requirements on plasma density and temperature as compared with its fusion counterpart. At the same time, it has benefited from many of the advances in plasma heating, control and confinement achieved in previous years. The Tandem itself, an open-ended linear device suffering from end-loss limitations in fusion, becomes particularly well suited as a variable I_{sp} rocket by virtue of such innate "leakage". Moreover, the experiments performed in the closing years of the U.S. mirror program reveal an intrinsic axial asymmetry and plasma flow which we seek to exploit.

Figure 1.

VASIMR Concept



PROJECT DESCRIPTION

As shown in Fig.1, plasma is generated and confined in the central cell of a symmetric magnetic tandem mirror. The device consists of a multi-coil central solenoidal cell with two high-field end-cells.

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4 F. R. Chang Díaz and T. F. Yang; Design Characteristics of the Variable I_{sp} Plasma Rocket. AIAA/IEPC 91-128, Oct. 1991

5 Franklin R. Chang; Hybrid Plume Plasma Rocket; U.S. Patent 4,815,279; March 28, 1989.

Plasma heating is done electromagnetically to both species: ions and electrons, by the well-known process of resonance heating. Operating and design parameters for the present system are shown in Table1.

Table 1

Device specifications:

Mirror field (LN2 cooled)	2 tesla
Central field	0.2 tesla
Central plasma radius	0.1 m
Vacuum chamber radius	0.18 m
Total length	3.2 m

High current magnet power supplies:

1500 kVA, 4160 VAC dedicated power.
Two 6-pulse phased controlled rectifiers 1 kA @ 400 VDC and 6 kA @ 150 VDC.
Multiple power supplies totaling 1.5 kA @ 40 VDC.

Vacuum tank exhaust dump: 1.5 m x 3 m.
RF and microwave power:

14 GHz klystron.	2 kW
2.45 GHz magnetrons.	2 kW
1 - 10 MHz RF transmitter coming on-line early 1997.	200 kW
3 - 1-30Mhz RF transmitters being reconditioned for future operation	3,000kW
Double half turn loop antennas, one in central cell and one in end cell.	

Data Acquisition and analysis:

3 Power Macintosh platforms, 1 Pentium PC.
LabView 4.0 with Jorway 411S drivers.
CAMAC Serial Highway with Jorway 411S driver and 5 crates.
GPIB communications.

While the present configuration is potentially capable of steady-state operation, it is unnecessary to do so at this time. The scope of this investigation centers on achieving stability at the much shorter characteristic times associated with rapid (microseconds) plasma disruptions. Typical discharges will last from 100 to 300 msec., while the magnetic field will be pulsed over periods of 5-10 sec., in essence achieving a flat-top level over the times of interest.

Eventual modifications to this device will include a novel, two-stage magnetic nozzle which expands and detaches the ionized flow from the magnetic field with a coaxial hypersonic boundary layer of neutral Hydrogen. The present system, including a cluster of RF transmitters (up to 3 MW.), a 6' by 10' vacuum chamber and all associated diagnostics and data acquisition systems are being assembled at the Advanced Space Propulsion Laboratory (ASPL).

Operation takes place at a base vacuum of 10^{-7} Torr., generated by two turbomolecular pumps located at both ends of the device. A large vacuum tank attached to one of the end-cells will provide a back-pressure plenum for future pulsed plasma exhaust experiments. In this configuration, gaseous Hydrogen (or Helium) is injected to pressure levels of 10-20 microns whereupon the magnetic pulse begins. As the field raises and achieves its flat-top value, the ECR and ICR transmitters are activated generating a plasma discharge which, if stable, remains radially trapped in the mirror. Plasma density and temperature data are extracted through Langmuir probe measurements and the presence and structure of H(alpha) emissions from the plasma column can be correlated to plasma stability.

For a given level of ionization, plasma density is a function of gas pressure. Our main objective is to explore the stable operational envelope of gas pressures and associated plasma densities and temperatures as the magnetic field flat-top value is varied.

RESULTS

Routine low power plasma operations in the lab were demonstrated in the spring of 1997. Typical Helium, Nitrogen and Argon plasmas can be generated at densities of 10^{11} particles/cc and temperatures of several electron volts. No plasma instabilities were encountered, thus paving the way for high power plasma discharges. Present level of effort centers on high power plasma operation, characterization, and system diagnostics. Low power plasma measurements in the central cell were accomplished in late 1997 with reciprocating Langmuir and Mach probes. A newly designed Lorentz Force Accelerator has been installed and successfully fired into the system as a high-density plasma injector. Other RF-based plasma injection devices, such as Helicon plasma sources have also been tested and are being considered for full implementation. A full, 2-D code, mapping the magnetic field throughout the entire machine has been developed. A Monte Carlo simulation which follows the trajectories of plasma particles in the magnetic expansion nozzle has also been developed.

AUTHOR'S NOTE

Due to the late submission, this report has been expanded to also reflect results obtained under our continued ASPL research program. Such research continues today as an internal NASA activity at the Johnson Space Center. The author's wishes to thank the administration of the University of Houston and the Space Vacuum Epitaxy Center for their patience and continued support of this research.