Primary Electric Propulsion is an appropriate tool for high-energetic interplanetary missions to provide the required velocity increments of more than 10 km/s considering missions like multiple asteroid rendezvous or comet nucleus sample return.

The work on the radio-frequency main propulsion engine RIT 35 has been resumed in 1984 under contracts of ESA/ESTEC and MBB company. After having carried out extensive performance mapping with mercury as the propellant, a second phase was started aiming at the inert gas performance of the RIT 35 with xenon as the propellant. After the indispensable refurbishment and improvement of the test facility, the RIT 35 motor has been modified for xenon introducing a new discharge vessel and a flow controller for the gas supply of the motor.

Performance mapping has been carried out with a flat extraction grid system which has been already used with mercury. Because of the well-known drawbacks of this system, MBB started the fabrication of a dished grid extraction system in parallel which will be made available for integration and tests in September 1988.

1. INTRODUCTION

Research work on radio-frequency ion sources started at the beginning of the 60's at Giessen University with the development of the 10 cm ion source RIT 10, which was designed for North-South-Station-keeping of geosynchronous communication satellites. After having finished the basic research work on the rf-thruster including optimization of the thruster components and plasma diagnostic investigations as well as experience in thruster operation, a scaling-up programme started beginning of the 70's basing on scaling laws and the experience with RIT 10 aiming at higher thrust levels and more powerful engines.

While the RIT 10 programme was supported financially by the German Government, the development of the larger motors was based on own fundings. Because of a lack of space programmes for the application of large ion thrusters, the work on these thrusters has been stopped 1977/78, and all efforts have been concentrated on the RIT 10 which has been ground-qualified completely in a comprehensive and very successful test programme at DFVLR (1).

Meanwhile, the scenario of scientific space missions has changed, and pretentious interplanetary missions are studied which require also an advanced propulsion strategy. Missions to primitive bodies as multiple asteroid rendezvous or a comet nucleus sample return require high velocity increments, which have to be provided during the mission and/or near the target (2) (3). This can be performed by an electric propulsion system delivering a 10 times higher specific impulse than the chemical one whereas the necessary escape velocity will be generated by chemical propulsion.

For such missions, thrust levels of up to 1 N will be required which can be done easily by clustering several ion propulsion systems of the RIT 35 type delivering 250 mN, each. The first RIT 35 experimental set-up, deduced from the smaller RIT 10, has been used for plasma diagnostics and optimization experiments. A laboratory motor with a partly open extraction system (750 holes) followed for preliminary performance mapping (4). Based on these results and experience, a laboratory model has been built at Giessen University in 1977/78, and later on at DFVLR Stuttgart in 1979/80. The tests proved that the 35 cm ionizer rf-thruster could be operated and controlled as easily as the smaller ones (5).

In 1984, the work on the large RIT 35 motor has been resumed at Giessen under funding of ESA/ESTEC and MBB company, respectively. In the scope of that program MBB studied the system design of an Electric Propulsion Module, and at the University of Giessen a laboratory model of a RIT 35 has been parametric tested using mercury as the propellant (6) (7). After the successful termination of these test contracts were placed in order to improve and adapt the test facility and the ion motor for xenon operation and repeat the performance mapping with xenon.

Furthermore, a dished grid extraction system should be manufactured and tested since the used flat grid system was misaligned during operation due to thermal stress. While the performance mapping with the flat grid system could be finished, the dished grid system has been assembled and integrated, and the first tests are planned in September 1988.

2. PARAMETRIC TESTING ON THE RIT 35 WITH XENON

2.1. Vacuum Facility

The largest test facility for ion thrusters at Giessen University is the "Jumbo" facility, a horizontal vacuum chamber, 5 m in length and 2.8 m in diameter, and a thruster hatch of 0.7 x 1 m which is separated from the main chamber by a large gate-valve.

The ion beam target is a water-cooled stainless steel cone surrounded by a large cylinder with fins which collects sputtered target material.

The chamber is pumped by two oil diffusion pumps of 50,000 l/s nominal pumping speed, each, and a conventional rough pumping system to a vacuum in the low 10⁻⁶ mbar range.

Prior to the test with xenon, the following activities were necessary:

- complete cleaning of the chamber from mercury
- removal of the liquid nitrogen cooled cryoliner
- improvement of the pumping speed for xenon

The first two actions could be realized easily but for the improvement of the pumping speed for xenon some effort was necessary. The available effective pumping speed of the diffusion pump is determined by the required baffle, the tubing, and the pumped gas and can be calculated for xenon to 8,000 l/s referred to a 50,000 l/s pump.

Theoretically, 16,000 l/s are available at the test facility which may be around 10,000 l/s actually. That is too poor to maintain a reasonable background pressure during thruster operation. For time and cost reasons, a decision has been taken in favour of two additional turbo-molecular pumps.

A large 5,000 l/s turbo-pump is mounted at the bottom
of the main chamber instead of a window and thus, supports the main vacuum system improving the effective pumping speed of the facility by about 30X.

A second smaller turbo-pump of 2,200 l/s is installed on top of the thruster hatch and is required to keep low pressure in the hatch around the ion motor. Formerly, the hatch was pumped from the main chamber through the gate valve but it turned out that the poor vacuum in the hatch caused breakdown in the rf matching circuit inside the hatch.

Both turbo-pumps are connected to the existing rough vacuum system with own control loops but they are not linked to the control board of the main pumping system.

Fig. 1 shows a cross-section of the Jumbo facility for xenon thruster testing.

2.2. The Ion Motor

Although the working mode of rf-ion thrusters has been described often, a short extract will be given here once again to point out the advantages of the radio-frequency principle.

The rf-thrusters is a very simple one, and the thruster itself consists only of a few parts that are the propellant supply, the discharge vessel, the extraction grid system, and the plasma bridge neutralizer (5).

The xenon propellant, stored in a high pressure bottle, is fed to the discharge through the gas inlet via a flow controller which measures and controls the desired gas flow to the thruster.

The ionizer vessel is made of quartz, and for oxygen it is longer than for mercury. Moreover, the downstream flange has been especially shaped to fit the old flat grid system as well as the new dished grid system.

The discharge vessel is surrounded by the induction coil which is connected to an rf-generator via an impedance matching circuit. The coil induces an electrical eddy field which transfers the rf-power into the annular, electrodeless, self-sustaining discharge.

This principle avoids any electrodes for plasma generation in the plasma and, consequently, all problems combined with internal electrodes like sputtering and erosion from the outset.

The ions are extracted from the plasma, focused and accelerated by a three-grid extraction system through 4227 holes. In order to reach the required high lifetime, all grids are very rugged, namely 2 mm thick, each. Besides, the accel grid is made of graphite which provides for extremely low sputtering rates. The decel grid is a closed electrode which guarantees a homogeneous beam potential and ion velocity, and it prevents neutralizer ions from impinging and damaging the negatively biased accel grid.

With a beam cross-section area of 880 cm², the RIT 35 motor provides for the highest thrust potentiality of all existing ion engines. Moreover, the grid system is designed for high extraction and beam voltages, and, thus, it allows high specific impulses as required by the high Δv missions.

The reported tests have been carried out with the flat grid system which was already used with mercury.

Due to thermal stress and expansion the grids changed their distance between each other, and sometimes a misalignment by a slight torsion of the accel grid has been observed.

To improve the mechanical and thermal stability of the grids, the MBB company has designed and manufactured a rugged dished grid system which has been mounted at the RIT 35 and is under test at present.

The plasma bridge neutralizers, which are mounted at the thruster case are taken from the RIT 10. At the rf-thrusters, the neutralizer has to fulfill two tasks, namely to deliver electrons for the ignition of the main discharge and then to deliver the electrons for the neutralization of the RIT 35 ion beam.

The electrons are generated in a small xenon DC-discharge and coupled into the ion beam through a plasma bridge which compensates the space charge and allows low coupling voltages between ion beam and the neutralizer. A second flow controller supplies the neutralizer discharge with the required xenon flow.

Fig. 2 shows a cross-section of the RIT 35 with the flat grid system and informs about the power supplies needed for the engine's operation.

Fig. 3 is the engineering model with assembled and integrated dished grid system, and Fig. 4 is a picture of the ion motor mounted in the hatch of the test facility ready for testing.

2.3. Power Supplies and Control of the RIT 35

As simple as the mechanical set-up are the requirements to the power supplies (see Fig. 2). The RIT 35 needs only three major supply units, a positive and a negative high voltage providing for the ion extraction and an rf-generator with an impedance matching circuit which sustains the discharge.

The impedance matching circuit is now equipped with a stepper motor driven remote control which allows the complete thruster operation from the main control board.

Besides, some auxiliary supplies are necessary as the ignition bias for main discharge start-up, the flow controller supply, and the neutralizer low voltage supplies for the cathode heater, the bias, and the flow controller.

The simplicity is also reflected by an extremely easy thruster control concept. For throttling up or down of the thrust level, it is enough to vary the rf-power but to keep high efficiencies, the mass flow rate of the propellant should be adapted simultaneously.

The variation of the specific impulse can be performed easily by changing the ratio of the high voltages but keeping the sum of both constant.

In principle, it is possible to use the software developed for RIT 10 automatic operation and control also for the large RIT 35 motor.

3. EXPERIMENTAL RESULTS

The functional tests on the RIT 35 with xenon have been carried out under two aspects

- to vary the beam current and determine the throttling range
- to vary the beam velocity and determine the range of specific impulse variation

The tests were carried out using the old flat grid system which caused some problems due to thermal stress and limited the range of parameter variation.
3.1. Throttling Range of the RIT 35

In order to figure out the throttling range, the basic thruster operations data must be mapped. For an rf-engine these are the rf-power consumption, the propellant consumption, and the extracted beam current which is the current to the extraction anode diminished by the drain current to the accel grid.

Fig. 5 demonstrates the rf-power consumption as a function of the propellant flow rate for different beam currents. In contrary to earlier test runs, the beam voltage has been kept constant at 1.0 kV achieving a specific impulse of about 32.5 km/s.

The rf-generator frequency has been set to 760 kHz which induces lower eddy current losses in the thru-hand side in the graph of Fig. 7.

However, trouble arose from arcing in the flat grid system beyond 2 A beam current. That phenomenon has been already experienced in earlier test runs with mercury and must be contributed to the thermal stress of the plasma holder. At higher power levels the plasma holder warps, the scaling between the grids is changed locally, and that finally causes the breakdowns. For that reason, the realization of higher thrust levels has been postponed until the dished grid system is available for testing.

Together with the dependence of the accel grid drain current on the mass flow rate, one can calculate the complete thruster performance.

The total power consumed by the rf-thruster $P_{\text{tot}}$ is given as the sum of the rf-power $P_{\text{RF}}$, the beam power $P_B$, the accelerator losses $P_{\text{acc}}$, and the neutralizer power $P_N$, namely

$$P_{\text{tot}} = P_{\text{RF}} + P_B + P_{\text{acc}} + P_N$$

From this follows the electric efficiency $n_e$ of the engine which is defined as

$$n_e = \frac{P_B}{P_{\text{tot}}}$$

The mass efficiency $n_m$ is given by the ratio of the ion beam equivalent flow $m_i$ to the total propellant consumption $m_{\text{tot}}$ that is:

$$n_m = \frac{m_i}{m_{\text{tot}}}$$

where $m_{\text{tot}}$ includes also the flow rate of the neutralizer. One achieves the total efficiency $n_{\text{tot}}$ by multiplication:

$$n_{\text{tot}} = n_e n_m = 0.98$$

where the factor 0.98 stands for beam divergence and beam homogeneity. A correction for double charged ions is not necessary since double charged ions could not be found in an rf-plasma due to very early diagnostic experiments using a mass spectrometer.

Taking into consideration the basic diagram and the above mentioned relations, one gets the graph shown in Fig. 6 which demonstrates the thruster power input as a function of the total propellant flow rate for thrust levels from 26 nN to 100 nN at a beam voltage of 1.0 kV which corresponds to an ion velocity of about 38 km/s. Two borderlines limit the range of operation of the RIT 35; the upper one is the highest rf-power which was available, and the lower one determined by the highest admissible mass flow rate.

Fig. 7 considers still the efficiencies and gives the total thruster efficiency depending on the propellant consumption. Parameter is again the beam current which represents thrust levels from 36 mN to 100 mN. The curves are limited by the already known factors, the rf-power on the left hand side and the discharge pressure or the mass flow rate on the right hand side in the graph of Fig. 7.

3.2. Specific Impulse Variation

Beside the thrust throttling, the range of the specific impulse is an important parameter in order to evaluate the applicability of an electric propulsion system for a given mission. The required specific impulse depends on the mission for which the thruster shall be used. It is quite different for North-South-Stationkeeping or orbit transfer, for an asteroid rendezvous or a comet nucleus sample return only to call some possible applications. Therefore, in the scope of the performance mapping on the RIT 35, the specific impulse has been varied, too.

The specific impulse of an ion thruster is defined as the propellant velocity which is given by the ion velocity multiplied by the mass utilization. That means, the specific impulse can be influenced by a variation of the ion beam voltage. This can be performed easily at the rf-thrusters by a variation of the positive high voltage (which determines the ion velocity) and a change of the negative high voltage but keeping the sum of both constant.

In this way, beam voltages from 1.0 kV up to 2.5 kV have been studied going up in steps of 500 volts. The influence on the thruster performance is depicted in Fig. 8 showing the basic curves, namely the discharge power as a function of the mass flow rate at a constant thrust level of 100 mN. The specific impulse for the demonstrated beam voltages ranges from 36.3 km/s up to 51.3 km/s calculated on the basis of a 0.85 mass efficiency for xenon ions.

In the way described before, Fig. 9 has been derived from the former one demonstrating the total thruster input power as a function of the mass flow rate for four different beam velocities at a constant thrust level of 0.1 Newton.

The influence of the efficiencies is shown in Fig. 10 graphing the electric efficiency versus the propellant efficiency for different ion velocities. Referred to the nominal beam voltage of 1.5 kV, the electric efficiency increases from 77% up to 85% at 2.5 kV beam voltage. Consequently, also the total efficiency is growing with the specific impulse starting with 94.5% at 1000 volts beam voltage and going up to 65% at a beam voltage of 2.5 kV.

4. CONCLUSIONS AND OUTLOOK

As already mentioned, the range of parameter variation during the test program was limited by problems with the flat grid extraction system. Due to thermal stress, the grid spacing was changed during the tests and finally, it was not possible to exceed a beam current of 2 A.

Also the breakdown voltage between the grids was reduced and led to difficulties especially at high mass flow rates.

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Several attempts to realign and readjust the grids were only a partial success since already after a short thermal load the grids were misaligned again.

Meanwhile, the dished grid extraction system has been manufactured and has passed already a shock and vibration test at MBB, Munich.

The final assembly and integration to the thruster will take place in the second part of September 1988. Then, the performance mapping will be repeated covering the complete range of operation of the RIT 35 ion engine.

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Fig. 1: Cross-section of the improved test facility P 100,000.

Fig. 2: Cross-section and power supply of the ion motor.

Fig. 3: Cross-section of the dished grid system.

Fig. 4: The mounted thruster ready for testing.
Fig. 5: Discharge power as a function of the propellant consumption for different beam currents.

Fig. 6: Total thruster power input vs. propellant flow rate for different beam currents or thrust levels, respectively.

Fig. 7: Total thruster efficiency as a function of the propellant flow rate for different beam currents.
Fig. 8:
Basic performance of the RIT 35 for different specific impulses.

Fig. 9:
Thruster power consumption for different specific impulses.

Fig. 10:
Thruster efficiencies for different specific impulses.