Design Development and Test of the RIT-μX Mini Ion Engine System

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Abstract: RIT-μX (Elegant BB) is a radio frequency ion thruster especially designed for the demands of high precision formation flying missions and the needs of fine and ultra-fine drag control. The thruster design bases on the experience in more than 40 years radio frequency ion thruster development. The RIT-μX thruster and system development has been performed in the frame of ESA’s GST program. This publication is focused on the results of the thruster functional test program. During the functional test campaign the basis performance (Isp, Thrust, Power consumption) as well as advanced parameters (Thrust resolution, Controllability, Thrust Noise) have been investigated.

I. Introduction

Miniaturized ion engines are considered as attractive solution to overcome difficulties and limitations of existing propulsion concepts for low and lowest thrust application. Especially, mini ion engines are bridging the gap between the only available fine thrust devices from FEEP type (μN range) and classical electric propulsion systems working in the mN range.

Mini ion engine systems will help to improve the system specific impulse and mission lifetime. They can provide highest thrust resolution, accuracy and controllability. Moreover mini ion engines are working with a very low level of thrust noise.

Astrium’s miniaturized propulsion solution is called RIT-μX. The name “RIT-μX” follows Astrium’s convention to label the Radio Frequency Ion Thrusters with an X as long as the thruster is in an early development status (see RIT-XT and RIT-22). The Greek “μ” emphasizes the special abilities of the engine for micro propulsion.
The work presented in this publication has been performed under a contract granted by the European Space Agency ESA in the frame of the GSTP programs. Under lead of Astrium Space Transportation, Business Line "Equipment and Propulsion" a study and development team has been formed bringing together the competences in all relevant fields. Astrium is a well known system house with a long term heritage in electric propulsion. For more than 4 decades a fruitful co-operation with Giessen University has been existing. The Radio Frequency principle was invented in Giessen in the early sixty's of the last century by professor Horst. W. Loeb, later-on a whole family of ion engine prototypes was developed under his lead [7][8][9].

During the last years Giessen University has focused its activities on micro-propulsion [1][3]. The successful work that had been performed [10] was the basis for the activities described here. Naturally, Giessen University is a strong partner in this project. Giessen University provides knowledge of thruster physics, scaling and layout. Moreover Giessen provides test services for development and endurance testing. Another experienced long-term partner in RIT development is the Institute for Surface Modification (IOM) Leipzig. The IOM has the lead for ion optics and lifetime analysis.

Although hardware activities are limited to the ion engine itself the RIT-µX project comprises system engineering too. An essential part for any ion engine is the required power supply and control logic (PSCU). Elaboration of the electronics system is performed by Astrium Satellites GmbH (Friedrichshafen). Design and layout of the flow management system is supported by University of Stuttgart, Institute for Space Systems (IRS).

This publication is focused on the functional test results obtained during the project. A more detailed description of the potential system has been yet published [11].

II. Typical low thrust missions

Reducing the altitude of earth observing satellites in low earth orbits evidently increases the resolution of the data from the measuring instrumentation. On the other hand the atmosphere's influence on the spacecraft increases.

A compensation of the atmospheric drag becomes mandatory. This is challenging for the propulsion system, as high thrust controllability and resolution is required combined with sufficient total impulse. Moreover the high amount of atomic Oxygen requires a robustness of the engine against this aggressive element. Concerns with respect to any technology which requires (hot) cathodes exists.

The installation of formation flying satellites forming one large virtual instrument offering a significant higher resolution than any large single instrument is considered as a break through for several types of (deep) space observation missions. Such experiments will deliver important impacts for fundamental physics and our understanding of the universe. For these formations again the controllability and the thrust resolution are from importance. High specific impulse and total impulse are highly desirable to maintain the experiments over years.

Ultra fine thrust control is required for some missions dealing with the measurement of gravity waves. Goal is a propulsion system with a thrust starting with zero to some tenth (hundreds) of micro Newtons. As these experiments will take place far from Earth, for example at the Lagrangian point L2 also a higher thrust in the range of some milli Newtons for the cruise phase to the destination is required.

III. The RIT-µX Ion Thruster Technology

A. RIT-µX Basics

Heart of the new RIT-µX small ion propulsion system is the radio frequency ion thruster RIT-µX with the unique electrodeless ionization of the propellant by electromagnetic waves. RF-ionization is known as a very effective way to ionise neutral gases. The implementation of this ionisation principle is very simple as merely two components are necessary: An ionisation chamber made of an isolating material and an RF-coil which surrounds this chamber. No other parts are required inside or outside the ioniser with respect to ionisation of the propellant! This makes the overall concept very simple, robust and erosion free.

If an RF-current is applied to the the thrusters RF-coil a primary axial magnetic field is induced inside the ioniser. This field generates a secondary circular electric field (E). Whereas the effect of this electro-magnetic field on neutrals or ions is negligible, free electrons gain sufficient energy for impact ionisation of the propellant: The propellant is set into the plasma state. Once the ionisation process is initially triggered the process is self-sustaining. All electrons required for a steady state operation are generated in the discharge itself. There is no need for an additional electron source, e.g. a main cathode, inside the ionisation chamber.
In ion thruster technology the rf-principle is unique, but there exists a broad field of applications where rf-ionization is used. It is employed in plasma- and ion sources for material processing (solid state physics, semiconductors, plasma chemistry...) as well as for neutral injector sources for fusion plasma heating. So the physics behind are well understood. Some special properties, which also apply for ion thrusters, make the RF-plasma very favourable for propulsion purposes and especially for micro propulsion.

B. Physical Background

*High Discharge Efficiency*: The plasma generation by RF is one of the most efficient methods to set a gas in the ionized plasma state. The efficiency is so high that no additional support, like external magnetic fields for plasma confinement is required. RF-thrusters work without permanent magnets or additional solenoid.

*Low Electron Temperature*: The plasma’s electron temperature is comparably lower than for Kaufman thrusters. Therefore the potential drop, which in a first order is directly proportional to the electron temperature, between the quasi neutral inner plasma and its surroundings remains below the sputter thresholds of the materials used for the ionisation chamber and the screen grid. *Neither the plasma sided grid nor the ionisation chamber are subject to any kind of erosion processes.*

*Low amount of multiply charged ions*: The power to thrust ratio of any gridded ion engine is increased, if multiple charged ions occur in the ion beam. A low electron temperature means a very small amount of multiple charged ions in the ioniser and the ion beam. *The low amount (typ. <1%) prevents sputter and erosion processes at screen grid and ionization chamber and ensures highest possible thrust efficiency.*

*Linearity between plasma-density and rf-power*: The plasma density is approximately proportional to the applied RF-power. This means that an increase of RF-power primarily increases the number density of ionized atoms instead of increasing the energy of the electrons (cf. electron temperature) and the amount of multiply charged ions. *Compared with Kaufman thrusters a smaller engine design is possible. It is the basis for a simple and effective thrust control strategy.*

*Inherent stability of ionization process*: The rf-plasma is inherently stable. Ions and electrons are generated inside the "bulk plasma", that means in the volume of the discharge chamber, the amount depends on the supplied rf-power. On the other hand electrons and ions re-combine at the surface of the ionizer vessel. The equilibrium between ionization and recombination is stable. As a result the RIT principle offers inherent, natural thrust stability.

C. Engineering and Application

*Limited Thermal Restrictions*: The RIT is the only known gridded ion thruster which operates without external static magnetic fields for the plasma confinement. For Kaufman-Thrusters this confinement is mandatory to achieve
an efficient ionisation whereas the magnetic field is necessary for ECR-Thrusters to establish the electron cyclotron resonance conditions. Using permanent magnets the operational temperature of the thruster is limited to the magnet’s Curie temperature $T_C$ which is typically in the range of 300°C. Some Kaufman-Engines omit the permanent magnets by using electromagnets with coils instead. The required number of turns for these coils makes an electrical isolation indispensable. Therefore the thermal restrictions are quite similar to that of permanent magnets. In contrast, the RF-coil of the RIT-Thruster is not covered by isolating materials because the distance from turn to turn is sufficient to achieve isolation.

*Inherent High Voltage Isolation:* The ionized propellant (plasma) is an excellent electrical conductor. So the high voltage provided to the screen grid (or an anode) is "visible" for any component in contact with the plasma. In case of the RIT this voltage is inherently isolated from surroundings. The non-conductive ionizer vessel is a natural barrier. In a RIT system only the cabling to the grid is on high voltage potential. In Kaufman engines also the entire cathode system and the anode are on high potential. Special care is required, also for the layout of the PPU where several modules are on high voltage potential [4].

*Thrust control:* The clear relationship between applied RF-power and extractable ion current and the inherent stability of the ionisation offer an effective thrust control strategy. Also without any regulation the beam current is constant as long as no other operational parameters alter (e.g. mass flow). For example, stability better than 0.3% over 100h was multiply demonstrated with the large RIT-22 engine. During this test no active thrust regulation was employed. With a simple closed loop between ion beam and RF-supply a high precision thrust control is realized. The stability only depends on the accuracy of the employed electronics. Neither external magnetic fields have to be controlled nor does any restriction by additional fields apply. Using high precision laboratory power supplies and the closed loop concept the thrust stability achieved with RIT-22 is better than $0.1\% \pm 1mA$ @ 2380mA beam current

*Ultra Fast Thrust Control:* If the rf-power is varied the ionization responses to a new equilibrium within some rf-periods. So within a few microseconds the thrust reaches a new state. The time thrust resolution of the overall propulsion system depends on the speed of the electronics around the engine. It is not limited by the thruster itself. In contrast to the rf-ionization any engines requiring cathodes are limited in there response by the thermal capacity of the cathode.

*Thrust noise:* The inherent thrust stability in combination with the fast thrust response offers excellent low thrust noise. The extreme low thrust noise is a challenge for any measurement.

### IV. RIT-µX Ion Thruster System

During the system design phase, architectures with two, four, eight and twelve engines have been investigated. The work was performed for three levels of thrust. In addition to the mini rf-ion engine also power supply and control unit PSCU and flow control system have been investigated in detail. Results are subject of the dedicate System Design Report. The description in this section is focused on the principle function of all mini ion engine system components.
A RIT-µX ion engine requires propellant and electricity for operation. The propellant flow to the engine is controlled by a flow control unit (FCU), the required electric power is provided by the power processing unit (PPU). The PPU controls also the FCU.

In contrast to the larger RIT engines like RIT-10 and RIT-22 it is possible to use gasless neutralizers, at least for low thrust (< 500 µN). Therefore no xenon flow management is required for the neutralizer. Furthermore it is not necessary to have one neutralizer dedicated to one thruster. It is important only that the total ion current expelled from all thrusters becomes completely compensated.

<table>
<thead>
<tr>
<th>RIT-µX Ion Thruster</th>
<th>PPU</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Expels ions and produces thrust</td>
<td>• Provides positive high voltage (defines beam potential and exhaust velocity)</td>
</tr>
<tr>
<td>Neutralizer</td>
<td>• Provide negative high voltage (optimizes ion extraction and prevents back streaming of electrons into the thruster)</td>
</tr>
<tr>
<td>• Emits electrons to compensate ion current from thruster</td>
<td>• Provide power for radio-frequency generator</td>
</tr>
<tr>
<td>Radio Frequency Generator</td>
<td>• Provide voltages for neutralizer</td>
</tr>
<tr>
<td>• Convert DC current into AC current (rf current)</td>
<td>• Measure and control beam current (thrust respectively) in close loop</td>
</tr>
<tr>
<td>FCU</td>
<td>• Provide voltages for FCU</td>
</tr>
<tr>
<td>• Regulate xenon flow to thruster</td>
<td>• Control FCU</td>
</tr>
<tr>
<td></td>
<td>• Exception handling etc.</td>
</tr>
</tbody>
</table>

Table 1 Components of a mini ion engine system

Please note: FCU, Neutralizer and PPU can serve multiple thrusters (cf. topologies). A detailed description exceeds the scope of this paper. For additional information refer to [2] [11] e.g.

V. RIT-µX Tests and Results

A. Overview

In August, 2008 RIT-µX was subject to an extensive functional test campaign. Highlights of the test campaign were:

- Performance characterization
  - Power consumption
  - Specific impulse
  - Thrust Range
- Pervane measurements
  - Dynamic range of ion optics (grid system)
- Electron back streaming test
- Thrust dynamics
  - thrust stepping
  - thrust linearity
- Thrust stability and noise measurement

These tests were embedded in a typical test program with mass inspections, electrical checks and visual inspections. All tests were performed in the Bic-Mac Test facility of the first institute of physics in Gießen. Gießen University also provided the flow control system and all required electronics. The setup included a beam current controller developed by the institute.

The ionizer and the carriers for the RIT-µX grid system are manufactured in alumina (ceramics). Manufacturing of these parts is time consuming. To avoid additional delays in the schedule, these parts have been additionally manufactured...
manufactured from macor. These parts were used for the functional tests because indeed the original alumina parts were not delivered in time.

It is anticipated that all data obtained during the functional test were in accordance with the predictions made in the study and design phase. However, the thruster performance using macor is lower than the performance using alumina. It means the data provided here are to be considered as "worst case". For the 1,500 hour endurance test the ceramic parts were used.

B. Performance characterisation

During the performance mapping the ion current is kept constant and the required rf-power is measured as a function of the xenon flow into the engine. The test is repeated for different current levels. Together with the power for the beam acceleration the total power can be derived. Finally the thrust is calculated and all data for calculation of thrust, power and total impulse are available Figure 3.

![Figure 3 RIT-μX Performance, Specific Impulse as function of total power and thrust level](image)

**Figure 3** RIT-μX Performance, Specific Impulse as function of total power and thrust level

**Figure 4** RIT-μX in operation

**Figure 3** shows, that the operational range is wider than the design target 50μN -500μN. Depending on the total power also operation with higher thrust level is possible. Even at the lowest thrust level the specific impulse is higher than 500s.

C. Electron back-streaming and perveance tests

1. Electron back-streaming (EBS)

   The negative potential in the vicinity of the second grid has to shield the positive potential of the inner screen grid. Otherwise electrons would be attracted and accelerated towards the screen grid. This must be avoided otherwise the screen grid could be damaged by the thermal load of the high energy electrons. In addition, for a given power budget, EBS would result in a reduction of the thrust. EBS might occur at high ion current densities in combination with high voltages at the screen grid. For low thrust operation at low voltages EBS is not an issue.

   For the EBS test an electron source was installed in the test chamber. Operational parameters of the thruster were set according to the test procedure. Than the negative voltage at the accelerator grid was reduced in steps of 5 V towards zero. The test was repeated for different thrust levels. It was found that the threshold for EBS is far away from the typical operational voltage of the acceleration grid. Furthermore it has been turned out that operation with a thermal electron emitter is less critical than operation with a hollow cathode for neutralization. In contrast to a hollow cathode which is able to deliver easily an additional amount of electrons the thermal gas less device is very limited in the maximum electron current. Even in case EBS conditions at the grid system occur the limited number of available electrons is an effective protection against EBS.
2. **Perveance test**

The perveance tests are intended for identification of the thruster's

- Direct impingement mode (prohibited for normal thruster operation)
- Nominal operation mode
- Over-crossing mode (prohibited for nominal thruster operation)

In both prohibited modes the acceleration grid is hit by ions with maximum energy gained in the electric field between the grids. The impingement of the fast ions results in a high erosion rate and severe grid damage.

The perveance test has shown that the useful ion optics range of the grid system is in line with the prediction: No indications for over-crossing or direct impingement have been found at the intended operational points.

D. **Dynamics**

1. **Controllability and thrust linearity**

   This section describes the dynamic features of a RIT-µX. Figure 6 illustrate a thrust stepping in the thrusters nominal thrust range from 50-500µN starting at an intermediate level of 250 µN the thrust was commanded down in steps of 50µN until the lowest nominal thrust level is reached. Then the thrust is increased in steps of same size until the upper (nominal) thrust level is reached. On each thrust level the engine is operated for 300 s

   The function between commanded thrust and engine thrust is plotted in Figure 6. A linear function describes the behaviour excellently.

2. **Thrust resolution**

   It is very difficult for some propulsion systems to follow small commanded steps of thrust variation as well as large commanded steps. Figure 7 shows the RIT-µX behaviour. The thrust was increased from 250µN to 500µN and vice versa performing the large 250µN jump. On the high 500µN thrust level micro steps (+/- 1 µN, +/- 2 µN, +/- 5 µN, +/- 10 µN) were performed. The thruster has mastered both tasks excellently.

3. **Thrust Noise**

   All thrust noise measurements were performed over night to minimize environmental impacts starting 19:30 in the evening and completed by 11:00 the following morning. In Figure 9 thrust versus time is plotted. The window used for data evaluation is marked with a blue box (12 hours). Typically, the thrust is constant in a band +/-0.1µN (0.02%). When the main door of Gießen Laboratory, where the facility is hosted, was opened the average thrust increases by 0.1µN. It is most probably caused by a small variation in the mass flow of the commercial flow controller. As the beam current controller is not optimized for 500 µN thrust it does not suppress the weak deviation of thrust.

   Data were recorded at frequency of 10 Hz. The result is plotted in Figure 10. The "electrical thrust noise" is lower than the requirements for LISA except peaks at 2 Hz. This is the frequency of the cryogenic pumping system. The probability that the effect is introduced via the grid system is considered low. As the coil is not hard-mounted to the thruster is can vibrate relative to the discharge vessel. For a clear identification additional work is required.
Figure 5 RIT-µX 50µN Thrust stepping

Figure 6 Thrust linearity

Figure 7 Thrust Stepping I - wide thrust range variation

Figure 8 Thrust Variation II - Small variations on the maximum nominal thrust level

Figure 9 Thrust vs. time plot for the 500µN

Figure 10 Thrust noise density - 500µN Thrust
VI. Conclusion and Outlook

The development of a RIT-µX miniaturized ion engine elegant breadboard model has been successfully completed. In an extensive functional test campaign the basic thruster performance has been mapped. For the desired thrust range, 50-500µN, specific impulse and power consumption are available. The performance has been mapped also for lower and higher thrust levels. When sufficient power is available on board the spacecraft, RIT-µX is fully operable in an extended thrust range. With pervance tests the full thrust range has been validated with respect to the dynamic of ion optics. EBS tests showed that the dangerous effect of back streaming electrons is not critical for small ion engines. Especially, when operated with a gasless neutralizer the maximum available electron current is limited. Moreover, the ion optics design shows ample margins.

Controllability and thrust noise are key issues for high precision low thrust systems. RIT-µX shows an impressive performance: The function between commanded thrust and thrust response is highly linear. The engine is mastering both small thrust variations and large thrust stepping. A thrust resolution better than +/- 0.1µN is found. The tests show clearly that that the limits for thrust resolution and controllability are given by the thruster electronics and not by the thruster itself.

Finally, first thrust noise measurements have been performed. The measurement shows an electric thrust noise even bellow the limits for ESA's challenging LISA mission.

In a first endurance test the engine has been operated for more than 1,700 hours at a constant thrust level of 500 µN. The results will be published in a separate document.

Meanwhile the European Space Agency has extended the baseline contract for the described activity. In the frame of the extension all steps for the RIT-µX qualification will be performed. Completion of the qualification is scheduled for the second half of 2010. In parallel, ESA has granted contracts for the development of thruster electronics (Astrium Satellites, Friedrichshafen, D) and a dedicated flow control unit (Nanospace, S). A coupled system test is planned before end of 2010.

References


55th International Astronautical Congress, Vancouver, Canada, Oct. 4-8, 2004


