DESIGN, CONSTRUCTION AND TESTING OF A VARIABLE ISP RADIO FREQUENCY MINI ION ENGINE TO BETTER SERVE THE PROPULSION REQUIREMENTS OF THE NEXT GENERATION GRAVITY MISSIONS “NGGM”

SPACE PROPULSION
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ABSTRACT:

Earth Observation as well as range of Scientific missions require fine attitude and orbit control by means of low-noise force actuators. Previously, it was demonstrated that Mini Ion Engines propulsion systems capable of combining high specific impulse and ultra-fine controllability can enable those requirements. However, more detailed look into the missions (and specifically Next Generation Gravity Mission) shows particular demand on increase of Specific Impulse (Isp) in lower thrust region which can’t be completely satisfied by the means of classical Ion Optic System (IOS). Variable Isp Ion Optic System approach was proposed to overcome this issue.

As a result, TransMIT GmbH was awarded an European Space Agency (ESA) contract to design, construct and test Ion Optic System for Radio Frequency Ion Thruster (RIT) engineering model developed in the frame of another ESA Technological Research Program (TRP) which would comprise full set of requirements for NGGM like mission.

The paper describes the proposed approach and its realisation. It delivers the results of performance testing of the Variable Isp Ion Optic System on a Mini Ion Engine RIT 3.5 including the endurance test. This paper also discusses the comparison between the original IOS and the newly built prototype as well as advantages of the concept application.

ABBREVIATIONS AND ACRONYMS:

NGGM	Next Generation Gravity Mission
IOS	Ion Optic System
ESA	European Space Agency
RIT	Radio Frequency Ion Thruster
TRP	Technological Research Program
RF	Radio Frequency
EP	Electric Propulsion

1. NGGM CONCEPT AND MISSION REQUIREMENTS

The next generation gravity mission is a mission based on fine attitude control and positioning of two satellites flying a formation flight. The necessary maneuvers for this mission impose strict requirements on controllability of the propulsion system of such satellites. Apart from the propulsive functions for the satellite-satellite tracking, the thrusters shall also compensate the atmospheric drag, as the mission measurement precision would profit from the flying in low attitudes, where the atmospheric drag can be a determining factor. The atmospheric drag in the NGGM mission relevant altitudes can be estimated to be between few hundred micro-Newtons to few mili-Newtons. As the maneuvers of satellite-satellite tracking require precise thrusts in the few ten micro-Newton regime, a very high thrust dynamics of a factor 50 between the minimum thrust and the maximum thrust is required [1]. This high dynamics together with the requirement for low power consumption, based on the fact that the satellite flying in very Low earth orbit cannot have large solar sells, and the very high life time of the mission (up to 7 years) face the thruster developers to a hard challenges.

Miniature radio frequency (RF) ion thrusters have been identified as candidate low noise actuators for the NGGM satellites. The precise, low and variable thrust provided by this type of thruster shall permit the lateral drag forces on the satellites to be compensated and also laser beam pointing control to the accuracy required for the mission. The higher specific impulse achieved by electric propulsion over cold gas propulsion also permits the total propellant for the mission to be minimized; mass restrictions and stringent noise requirements in fact prohibit the use of chemical propulsion for NGGM.

Table 1 summarizes the propulsion requirements for the lateral thrusters as identified in the system studies [2-3].

Tabelle 1: Propulsion requirements for NGGM

Parameter	Unit	Collinear Lateral Thrusters
Minimum Thrust	mN	0.05 (0*)
Maximum Thrust	mN	< 3
Thrust Resolution	μN	0.5
Thrust Noise		<1μN/√Hz above 0.08Hz
Rise/Fall Time	ms	< 50
Slew Rate	mN/s	> 0.5
Update command rate	Hz	10
Thrust non linearity		< 2%
Lifetime	yr	> 10
Specific Power	W/mN	< 40
* Thrust has to be turned off completely if thruster is not operating		

2. RIT 3.5: ORIGINAL ENGINERING MODEL

An Engineering model of the Radio Frequency Mini Ion Engine RIT3.5 was developed by TransMIT GmbH according to the Propulsion Requirements of the Next Generation Gravity Missions between 2013 and 2015 in the frame of ESA contract "Miniaturised Gridded Ion Engine Breadboarding And Testing For Future Earth Observation Missions". Various aspects of plasma, electromagnetic and thermal models of the thruster for the comprehensive radio frequency gridded – ion thruster modelling used to develop RIT3.5 are described in [4]. Broad Characterization test campaign confirmed overall compliance of the thruster to the mission profile including also thermal status with some limitations. Tests were performed in two different Electric Propulsion (EP) facilities to eliminate facility effects. Endurance test campaign demonstrated however that further investigations are required to prove whether lifetime of RIT3.5 is as well relevant to the very high requirements given. Details of the project and its achievements are summarized in [5, 6, 7 and 8]. Figure 1 depict the thruster assembly.

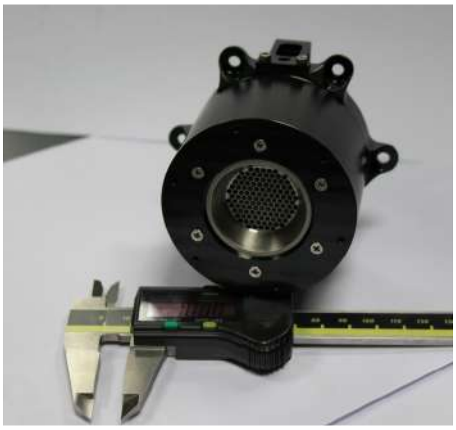

Figure 1. RIT 3.5 developed by TransMIT GmbH

The follow up project was granted to TransMIT to propose new solution for an Ion Optic System that would allow thruster to meet the following criteria:

- Allow broad variation of the thrust from low microN to 2 mN;
- Allow independent control of Specific Impulse in the full thrust range;
- Demonstrate lifetime not lower than Grid System of original thruster aiming to fullfil NGGM requirements;
- Would be easy to implement.

3. ION OPTIC SYSTEM

In the Gridded Ion Engines (GIE) processes of plasma generation and thrust production itself are conditionally divided and thus can be investigated separately in a first approximation. No matter how the plasma production is, thrust is always generated by the extraction of ions from the plasma discharge and their acceleration by means of the electrostatic field generated in a special unit – Grid System, which for similarity of process to an optical system is named Ion Optic System (IOS).

In order to change the thrust, an increase or decrease, it is necessary to manipulate the positive high voltage applied and/or the grid open area (transparency or size of the thruster), and/or the current density, according to the required change: increase or decrease.

The grid open area together with other geometrical grid parameters – aperture sizes and interspaces - are normally being set on base of the minimum and maximum thrust requirement. Full thrust range should be achievable on the same geometry as no changes of these parameters can be applied throughout thruster operation. With fixed grid geometry voltage drop between screen and accel grid is the only variable parameter defining both ion current extracted and thrust. In a classic IOS accel grid voltage is practically forced to be fixed, thus only positive high voltage stays for variable. Unfortunately, change of positive high voltage will also lead to specific impulse change.

Surely, for every set of IOS geometry and voltage distribution current density might be varied also by variation of discharge parameters depending on RF power and mass flow but only in a narrow range also.

Summarising, the Specific Impulse and Thrust of the real thruster with classic Grid System are interdependent and no practical variety of Specific Impulse can be proposed for fixed thrust levels. Thus, to give the Ion Engine ability of independent control on Thrust and Specific Impulse new techniques was introduced.

The idea is based on the use of additional electrode inside of IOS in order to de-couple extraction and acceleration as it has been originally proposed by D. Fearn for use on the Ion Engines. Such method allows breaking the limitations and accelerating extracted ions to higher velocities, meaning gain higher numbers of thrust and specific impulse of engine [9].

In 2011 MAI initiated study aimed to demonstrate other opportunities which four-grid system could introduce to GIE technology: flexibility of thruster performances optimization and lowering power to thrust ratio by redistributing potentials and/or optimising geometry of grid system. Number of experiments was performed that confirmed multiple assumptions of researchers. Particularly, it has been shown that the method of using four grid-system is able of providing different ion currents or thrusts by the same Isp which also can be chosen[10].

4. RIT 3.5: VARIABLE I_{SP} ASSEMBLY

Use of additional fourth electrode in order to be able to redistribute potentials in the IOS and thus manipulate with extracted current and energy of ions separately was proposed to fulfil ESA project requirements.

As original RIT 3.5 had three grids already, it was comparably easy to implement this way as it was only necessary to add electrode on thruster output. It has been decided to use encircling ring instead of over complex design adding extra grid as it is only necessary to apply ground potential in order to separate potentials inside and outside thruster.

In order to keep heritage of RIT 3.5 and be able to use its test results it was decided to keep geometry of IOS of original 3 grid thruster as is.

Performance model was developed to predict performances of the thruster with new IOS. After preliminary modelling design of the new grid system has been carried out. Figure 2 demonstrates integrated Variable Isp Ion Optic System on RIT 3.5 EM.

Figure 2. RIT 3.5 with Variable Isp IOS developed by TransMIT GmbH

5. EXPERIMENTAL RESULTS

Figure 3. R2D2 test facility

In the frame of the project, an extensive experimental program divided in two sequences of characterisation and endurance tests was foreseen. Characterisation tests, included performance mapping. Endurance test included 500 h of direct firing of the thruster with three erosion measurements with the help of microscopy before test kick off, after 300h of firing and at the end of the test.

Test campaign was done R2D2 vacuum test facility (depicted in Fig. 3) of TransMIT GmbH located in Ludwig Bölkow Campus, Munich. This facility comprises two volumes – main chamber and hatch with total volume 4.5 m^3 and total pumping capacity of 24 000 l/s.

The most challenging part of the thruster requirements for NGGM was the very large dynamic range of the thrust which had to be demonstrated in the frame of characterisation test campaign. The minimum thrust was required to be around 50µN and the maximum not less than 2000µN. The Figure 4 shows the results of the thrust range achieved in the frame of such tests in comparison to predicted values: power consumption of the thruster for different thrust levels.

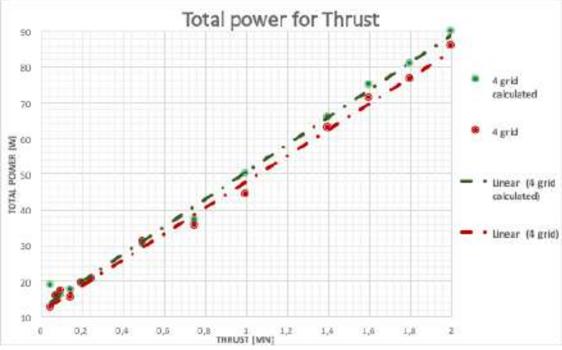

Figure 4. The power consumption of the thruster for different thrust levels between 50µN-2500µN

During the experiments there has been no evidences on the limitation of the thrust minimum and a maximum thrust of 2500µN were achieved (alothough no trials to go over this value was done). Figure 5 shows the thruster Isp for different thrusts in comparison to predicted ones.

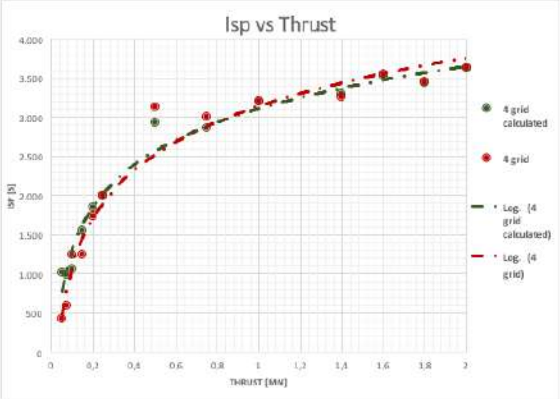

Figure 5. The Isp of the thruster for different thrust levels between 45µN-2500µN

Figure 6 shows variation of thruster Isp for different thrust levels experimentally derived for RIT 3.5 with Variable Isp IOS (green) and original RIT 3.5 EM assembly.

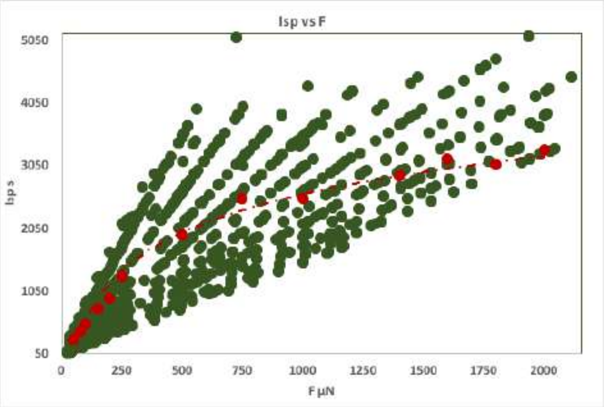

Figure 6. The Isp variation of the thruster for different thrust levels between 45µN-2500µN. Green – Variable Isp IOS; red – Original IOS.

As can be seen Isp variability has been achieved with the help of newly built IOS that allows expand thruster performances.

The power consumption at the thrust level of 2 mN differed between 75 and 100 Watts, which allowed a power to thrust ratio below 40W/mN at bus level. Specific Impulses variation shown for 2 mN was between 3000 s and 5000 s.

The power consumption at the thrust level of 50 microN differed between 6 and 25 Watts, while Specific Impulse variation shown was between 100 s and 500 s.

6. SPECIAL CONSIDERATIONS AND CONCLUSION

A modular extraction system was designed, constructed and tested. This grid system allows relatively independent regulation of the thrust and Isp in mini Gridded Ion Engines in a very bright thrust range as from 50 microN to 2 mN satisfying also demand on low power at different thrust levels. Low power consumption is especially important due to the small solar cell arrays on NGGM spacecrafts that would also ensure the minimizing of the heat production in the thruster. Designed Ion Optic System was manufactured and tested showing a very good compliancy of the experimental results to the requirements.

An endurance test of 500 hours has been performed in order to validate grid erosion rates predicted by ion optics simulations and expected to be lower than one achieved by original RIT 3.5 IOS.

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GRID SYSTEM FOR LOW-POWER ION THRUSTERS

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