A Nouvelle Neutralization Concept for RIT-µX Miniaturized Radio Frequency Ion Thruster Systems

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Abstract: ArianeGroup GmbH is developing a neutralizer with rf-ionization instead of thermionic electron emitters for their RIT-µX propulsion system. The RIT-µN neutralizer is designed to serve multiple RIT-µX thrusters at the same time. An introduction in the RIT-µX concept and its typical applications is given followed by a discussion of the basics of neutralization. RIT-µN is described and the corresponding test program is presented. The test program is part of a project in the frame of the European Space Agency's Global Study and Technology Program. A brief summary of the project completes the publication.

I. Introduction

The RIT-µX is a small radio-frequency ion thruster designed for the Micronewton and low Millinewton thrust range. High specific impulse, high reliability and perfect thrust control are the advantages of RIT-µX based propulsion systems. Applications are the in-situ compensation of atmospheric drag for spacecraft in low earth orbits or the compensation of the solar drag at the Lagrangian Points. RIT-µX is also considered as an excellent solution for formation flying and the realization of "distributed instruments". Besides scientific application RIT-µX is an attractive propulsion solution for mini - and small satellites. Even the use as an actuator for tele-communication satellites can be considered.

RIT-µX is the smallest member of the Ariane Group radio-frequency ion thruster family. It is a downscale from the flight proven RIT 10 which synthesizes heritage and the results of contemporary developments.

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The initial development of RIT-µX was triggered by the needs of the European Space Agency's scientific missions. Over the time, different ranges of thrust of interest (50µN-500µN, 10-100µN and 50-2500µN) were identified[1,2,3]. For all three thrust ranges TRL 5 has been successfully demonstrated in corresponding ESA programs.

For all the thrust ranges the design of RIT-µX remains the same and merely the thruster's grid system is adapted to the new requirements. This generic approach reduces development costs and allows the usage of one and the same radio frequency generator independent from thrust range.

Meanwhile the generic thruster concept is evolved a further step: Operation of an adapted RIT-µX in a "reversed mode" enables RIT-µX working as cathodless neutralizer for RIT-µX systems.

When the RIT-µX project begun the focus was on its medium thrust range (50-500µN)[4]. At 500µN the ion current per engine remains below 7mA. For this current, qualified thermionic neutralizers developed for ESA's MICROSCOPE mission were available. Later ESA system engineers asked for a further reduction of the thrust down to 10-100µNs only (e.g. LISA Pathfinder Mission). In this case one thermionic device is capable for compensation of the ion current of multiple RIT-µX thrusters.

However, RIT-µX is a versatile device. With the development of the third ion optics system the engine delivers up 2mN thrust (3mN peak). It means also that the max. ion current per thruster is 4-6 times higher than at the beginning of the development activities. Although Ariane Group and partners have demonstrated that the thermionic neutralizer from MICROSCOPE can provide the neutralization current, when the device's second redundant emitter is used nominally, it is obvious, that the upper limit of its capabilities is reached.

For larger ion engines, hollow cathode neutralizers are de-facto standard. These devices are available in different sizes. For their operation, xenon is required. Typically, a neutralizer requires about 10% of the main engines Xenon flow. Although they are well scalable for ion currents starting at some 100mA up to several amps, it turns out that the downscaling has a limit. It is the diameter of the orifice, which cannot be reduced linear with the electron current. A minimum diameter is necessary to ensure that the plasma bridge from the inner part of the neutralizer with the thermionic insert to the environment can exist. This means also, that the minimum xenon flow which is linked to the orifice diameter cannot be reduced below a certain threshold. The consequence of this fact is, that the smallest available hollow cathode neutralizers would consume more xenon than the RITµX thruster itself.

It is the gap between the thermionic neutralizers working well in the Milliampere range and the hollow cathodes which efficiently work starting at some 100 mA that motivated the search for a new concept. It turned out that the rf-principle itself is very promising for this intermediate electron current range.

With the decision for RF-neutralization a second decision has been made: The neutralizer for RIT-µX systems should not be fully a new development. Instead, the clear design goal was using exiting parts from RIT-µX, wherever possible.

The next chapter will introduce into the radio-frequency ion thruster principle and -systems. In Chapter III the fundamentals of neutralization are briefly discussed. Then, we are ready for a more detailed description of the RIT-µN development.

II. RIT-µX Propulsion Systems

A. RIT-µX Thruster

Key element of the electric propulsion system is the radio-frequency ion thruster RIT-µX. The radio-frequency ion thrusters belong to the class of gridded ion engines:

All gridded ion thrusters generate thrust in two steps. In the first step the propellant is ionized. In the second step the ionized fraction of the propellant is accelerated in an electrostatic field of an ion optics system ("grid system"). The ion acceleration in a grid system is the common feature of all gridded ion engines. However, different types of ionization are used.

RIT-µX is a miniaturized thruster derived from the RIT family ion thrusters. Radio frequency thrusters ionise the propellant in an oscillating electro-magnetic field. The propellant enters the ionizer via an integrated insulator and gas distributor. The ionizer vessel is made of an insulating material (quartz or alumina), and it is surrounded by the induction coil.

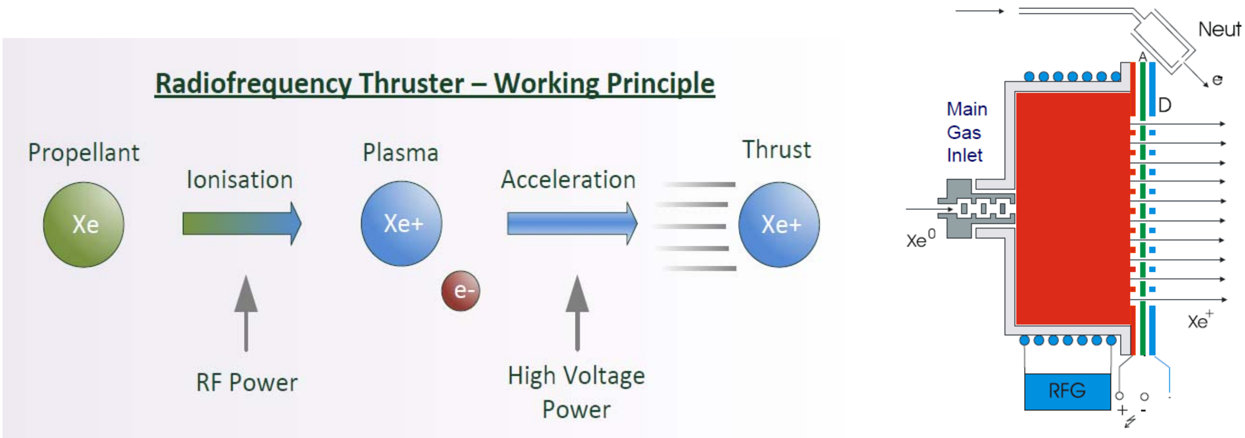

Figure 1 Working principle and realization of RF-Ion Thrusters

The axial magnetic field of the rf-coil induces a circular electrical eddy field, which accelerates the discharge electrons and enables them to ionize the Xe-atoms by inelastic collisions. Thus, an electrodless, self-sustaining rf-gas discharge (plasma) is generated. By thermal movement ions from the bulk plasma find the way towards the grid system.

Eventually, the ions are accelerated in a system build-up of two grids. Concentric holes in these grids form a large number of single extraction channels. Every of these channels is a single ion optical system. The ion optical system's properties are determined by the diameters of the holes, the grid spacing and the applied voltages.

The rf-principle has been selected because it provides inherent advantages, especially for miniaturized, high precision thrust devices:

- Very good scalability
- Fast thrust response
- Excellent thrust controllability
- Low thrust noise
- Direct electric feedback of produced thrust
- Working with inert noble gas xenon
- Free of (magnetic) torque

Besides the functional and performance advantages the rf-principle simplifies also the design of the corresponding Power Processing Unit (PPU). High voltage is feed to the grid system only. There is no back propagation of high voltage via the ionized propellant (plasma) inside the ionizer to the system. High voltage is inherently insulated by the ionizer chamber made of a non-conductive material.

B. RIT-µX and embedding System

The system key element, the miniaturized ion thruster RIT-µX requires propellant and electricity for operation. The propellant (Xenon) is stored in a tank. In a first step the Xenon flow control system reduces the high pressure from tank down to typ. 2bar. In the next step the flow to each thruster is controlled, individually. The Xenon flow control system is electrically linked with and operated by the power processing unit.

The PPU provides all voltages required in the electric propulsion system. It converts the voltage from spacecraft power bus, provides a telemetry interface to the spacecraft data bus, manages exception handling and enables autonomous system operation.

Eventually, thrust is produced in the radio frequency ion thrusters. As described before, the RIT thrusters ionize the propellant using electromagnetic fields. The ionized propellant is accelerated in the thruster's ion optics system.

The required alternating current (AC) is supplied by radio-frequency generators (rf-generator). An rf-generator converts a DC current (from PCU) into an AC current.

An ion thruster expels only positively charged particles (ions). Thus an electron source is required to prevent the spacecraft from getting charged. A device called 'neutralizer' provides the necessary amount of electrons.

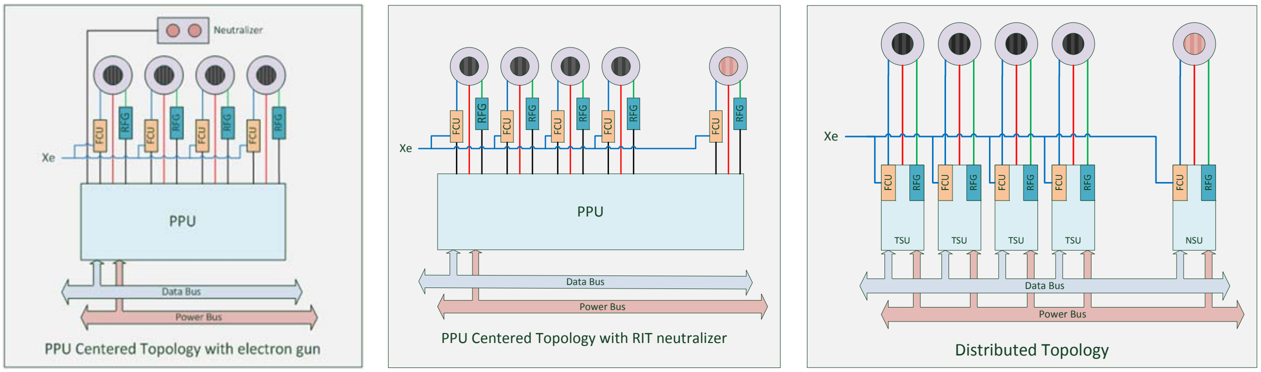

Figure 2. PPU Centered Topology (left, middle) and Distributed Topology (right)

For RIT-µX systems two different system topologies can be realized: For scientific applications, which demand a fast and precise control of multiple thrusters, the classic *PPU Centered Topology (PCT)* is favorable. In this topology, one PPU controls up to four thrusters and one or two neutralizers.

Once the system is qualified, any modification will require re- or delta-qualification. This approach is sensible for sophisticated scientific applications with very mission specific requirements. However, for small and mini satellites where the requirements for the thrust quality are relaxed, and basically the number of thruster varies, a more flexible approach is the *Distributed Supply Topology DSP*. In this topology each thruster has its own control module and the same applies to the neutralizer. Whether PCT or DSP fits better to the customer needs depends on both, technical and economic factors. For example, when the command interface is to be implemented via MIL 1553 Standard, this is of high effort and the DST approach becomes obsolete [5].

All topologies depicted in Figure 2 have only one neutralizer for four engines in operation. This might surprise because from larger engines we are used to have a dedicated neutralizer which is either integrated in the thruster or at least in close vicinity to the engine. In this context it is worth to recapitulate the three basic types of neutralization.

The highest degree of neutralization would be a direct recombination of one electron with one ion leaving one neutral atom. However, this will rarely happen. The two fundamental physical laws, conservation of momentum and conservation of energy have to be fulfilled at the same time to allow direct recombination. The probability that this process can take place is extremely low. So what happens if we have a source for electrons and a source for ions on one spacecraft and we cannot achieve recombination?

The best case that we might achieve is a mixture between both species in a way that space charge becomes compensated. However, even that is of lower probability. In fact measurements and simulations show, that the electrons from neutralizer will travel in a helix around the ion beam in the center. So we rather have two independent currents than one neutral mixture of species.

As both species remain decomposed from each other a third concept of neutralization seems natural: It is a simple current compensation. We have to ensure, that the same amount of electrons and ions is expelled anytime and that is it. In this case neutralizer and thrusters can be delocalized. It is a very useful concept, when we have multiple low thrust devices on a spacecraft firing either simultaneously or individually.

The current neutralization concept is space proven. It was demonstrated on ESA's technology satellite ARTEMIS, when one ion thruster was operated on the south platform and the neutralizer on the opposite side.

The concept is not applicable for thrusters which need the electron source also to maintain their main discharge (e.g. Hall Effect Engines).

III. RIT-µN Neutralizer

In principle, there are two options to 'get electrons out of an rf-neutralizer'. Their physical nature is from fundamental difference. This has impact on implementation and operation. The electrostatic electron extraction can be understood as reverse of ion extraction. It requires two grids in series and active electron current control. The plasma bridge extraction requires only one grid and inherent self-adjustment to the ion current of the thruster is achievable.

Electrostatic Electron Extraction (EEE)

Both electrons and ions find their way into the plasma sheeth by random (thermal) movements. Do to the potential between the inner plasma and the surroundings the electrons are decelerated and the ions are accelerated. The potential self-adjusts balancing the two currents to zero in sum. Electron and ion current passing the sheet are equivalent.

For ion extraction the potential at the first (inner) grid is set positive and the potential at the following second grid is negative. Ions are accelerated in the electrostatic field between the two grids whereas electrons are repelled.

When the polarity between the grids is reversed the electrons are accelerated and the ions are repelled.

For both electrons and ions the "Langmuir-Schottky-Child-Law' is applicable: A certain voltage is required to drive a current through the grid also for electrons. The $j \propto U^{3/2}$ relation between current density j and the voltage U remains valid.

Contrary to the setting for ion extraction (high absolute voltage at the first grid) the negative potential at the first grid shall be low. Otherwise the electron extraction would contribute to the power budget in the same way than the ion acceleration in an ion thruster.

The positive potential of the second grid will 'push away' all ions from the neutralizer surroundings. This will make the coupling of electrons to the plasma around the spacecraft difficult. For that reason a third grid on or slightly below satellite potential can be implemented.

Plasma Bridge Extraction (PBE)

Consider a compartment with plasma inside: The compartment has one single aperture towards its surroundings.

Inside the compartment one will find a plasma sheath between the bulk plasma in the volume and the surface of the compartment. The thickness of the sheath depends on the plasma parameters electron temperature (T_e) and plasma density n_i. For typical RF plasmas the sheath thickness does not exceed few tenths of a millimeter.

If the inner diameter of the aperture is larger than two times the sheath thickness, the bulk plasma will penetrate into the aperture. Along the aperture axis the plasma density will decrease due to the losses at the aperture's surface. The result is a gradient in the aperture which transports ions and electrons through the aperture.

In case of a positive potential outside the compartment, electrons will be transported through the aperture. This transport mechanism is not space charge limited and much higher (electron) emission currents can be realized.

Comparing both methods it is essential that the neutralizer works in plasma bridge mode. Beside the avoidance of a second grid the decisive advantages are the comparably higher electron current and the coupling of the neutralizer to the plasma of its environment. The latter is also the key for the self-biasing of the electric propulsion subsystem potential such that electron- and ion current will be inherently balances without any additional need for a control loop.

RF-Neutralizer Ion Catcher

Independent from the extraction mode a collector for ions is required inside the ionizer. This ion catcher has to gather an ion current equivalent to the electron current leaving the neutralizer in EEE- or PBE-Mode. The current to the catcher is limited by the Bohm-criteria. It means, that the ion current density to the catcher is the same that we can expect upstream of the grid system in an ion thruster. Especially, compared with the high dense PBE electron current it is much smaller. It is necessary that the catcher is sized accordingly. The area of the catcher surface multiplied with the ion current density has to be equal to the maximum required maximum total electron current.

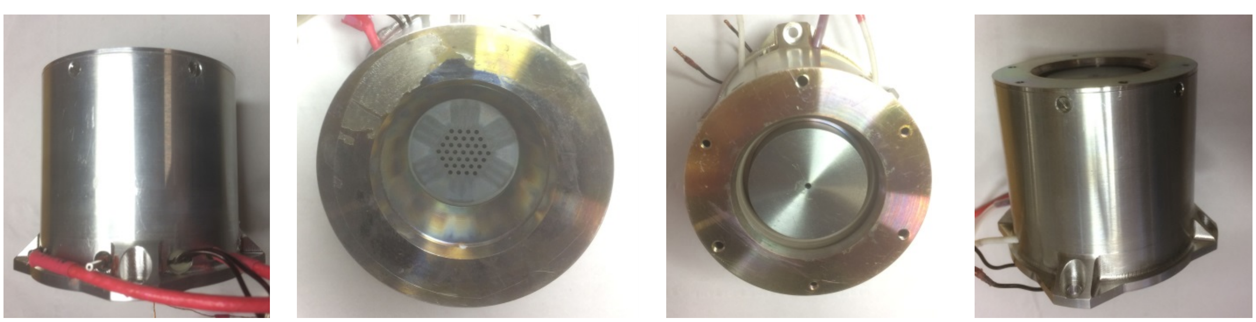

Figure 3. RIT-µX Thruster (left, middle left) and RITµN Neutralizer (middle right, right)

Implementation

Figure 3 shows both RIT-µX thruster and RIT-µN neutralizer. Both devices look very similar and in fact, the primary design development objective, maximum reuse of RIT-µX part has been achieved. All major elements, from structure, interface section to ionizer remain unaltered. Also the grid carrier assembly is the same. Instead of the screen- and accelerator grid it holds the ion catcher which also included the orifice.

Besides scale factors in production the alikeness of parts in RIT-µX and RIT-µN provides further advantages. Main heat source in both devices is the ionizer unit which is identical. Thus the RIT-µX thermal model is applicable for RIT-µN with only minor adaptations. The same applies for the structural model.

IV. Test Program

The RIT-µN test program consists of several elements. In an initial test campaign the neutralizer is tested as standalone device. In the next step, RIT-µN is tested together with a RIT-µX thruster. An 2,000 h endurance test will complete the test program.

All functional and performance tests are conducted in Gießen University's BigMac EVO facility. BigMac EVO is the upgrade of the well- known BigMac facility. After the upgrade the facility has a length 3,2m. The diameter remained 1,6 m as before. The facility is equipped with a cryo-system providing 34,000 l/s (Xe) pumping speed in total.

Figure 4 BigMac EVO Test Facilities

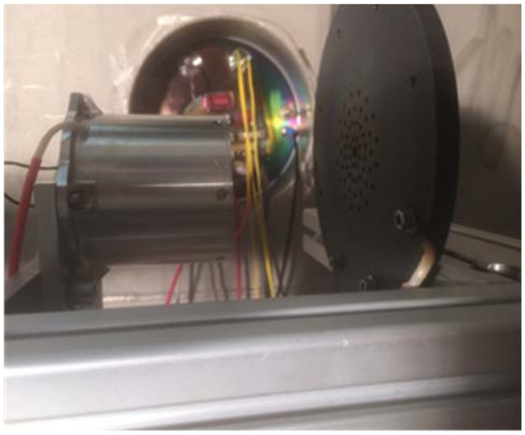

Figure 5 RIT-µN with Anode

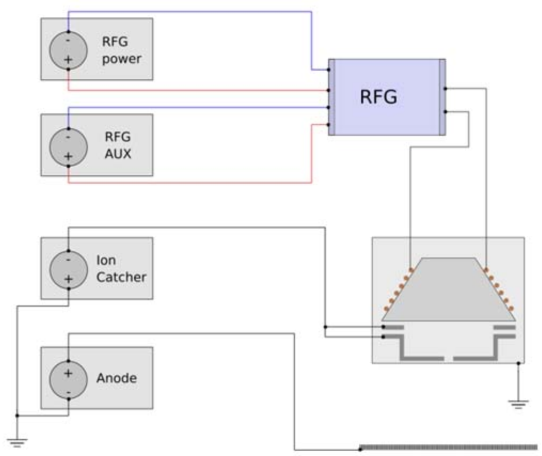

Figure 6 Electrical Test Setup

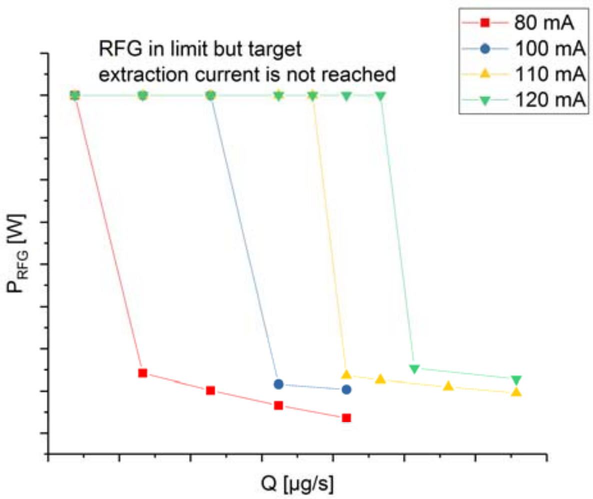

Figure 7 First Result from Performance Mapping

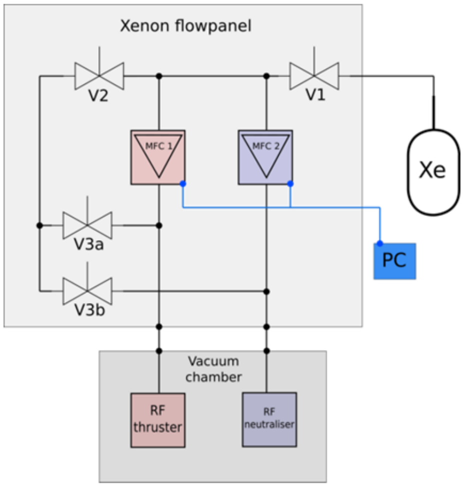

Figure 8 Flow schematic

Figure 9 Coupled test - RIT-µN (left) and RIT-µX (right)

Performance Test

Figure 5 shows the RIT-µN neutralizer together with an anode plate installed in the BigMac EVO facility. The electric setup is depicted in Figure 6: The neutralizer internal ion catcher and the anode are connected to DC power supplies. The catcher can be biased negative with respect to test facility ground ("mains") whereas the supply for the anode enables a positive bias voltage.

The RFG needs two supplies for operation. A small 12V auxiliary supply feeds the RFG control logic and PLL circuit, the power stage is connected with a second supply. This supply controls the RF-Output power/current respectively.

The xenon mass flow is measured and controlled using a commercial mass flow controller (Bronkhorst EL-FLOW 1.5sccm). As mass flow controllers (MFC) might lack accuracy, especially, when operated in their lower flow regime, the mass MFC was cross checked by direct mass measurement and a calibration table was established.

The xenon comes from a standard gas bottle. The pressure is reduces down to ~0.5 bar. The MFC is controlled using a PC. The flow schematic is depicted in Figure 8.

During a performance map the bias voltages for catcher and anode are kept constant. The flow rate is commanded to the highest value of the test series and the rf-power is adjusted that the desired electron current is obtained. Then, the mass flow is reduced step by step. The procedure is repeated for different levels of electron current.

Only a weak increase of RF-power is observed until at a certain value, the RF-power suddenly increases (Figure 7). At this point it is not possible to extract the desired current. The discharge inside the ionizer remains stable. If the neutralizer were operated in DC space charge mode, we would find continuous operation. It is noted that mass flow for break down and snap in show a pronounced hysteresis. The entire behavior shows that the neutralizer is operated in the desired plasma bridge mode.

Despite plasma bridge mode operation the required rf power shows still a dependence of the bias voltage setting. This leads directly to the question: "What is the representative bias voltage ("CPR") in a real system where the neutralizer expels electrons to an ion beam or to space? The initial settings were chosen according the experience with hollow cathode neutralizers, but the question remains: Is this approach is really representative?

In consequence it was decided not to complete the performance mapping until a large matrix of operational points is filled. Instead, the coupled test was preponed. Figure 9 shows neutralizer and thruster in one dedicated setup. The test is still running and data evaluation is ongoing. However, the two most important findings are reported:

1.) Also without the 'hard' anode electron extraction is possible in plasma bridge mode
2.) Figure 9 shows a configuration in which the neutralizer is tilled towards the thruster, however plasma bridge mode can be sustained also when the axis of both devices are parallel or when the devices are delocalized
3.) The absolute voltage in floating mode operation is some volts only

Findings 1.) and 2.) are important bricks for the prove of concept. The third finding is interesting from the physical point of view. One possible interpretation is, that the potential drop from the plasma potential is sufficient.

V. The MRGAN project

As written, the test activity is embedded in an ESA GSTP project. It is called 'Miniaturised Radiofrequency Generator and neutralizer for RIT-uX' (GSTP 617-145 MP) or MRGAN for short.

A further specific key element in any RIT based system is, besides the thruster, a suitable radio-frequency generator. In fact, thruster and rf-generator represent a functional unit. In this view, the rf-generator can be considered also as a part of the thruster itself.

Ariane Group labels the rf-generators according to their DC input power ('RFG-XX'). Starting with the so called RFG-40, succeeding models have continuously improved performance and functionality. With 'RFG-60 Advanced', which was developed in context of the LISA Pathfinder technology demonstration activity, both performance and function have reached their targets.

In the frame of the MRGAN project a further miniaturization of the device is requested. The development team targets on a mass of 300g and a size of 130 mm x 106 mm x 29 mm including the area for mounting screws. In fact that represents a reduction of the RFG volume by a factor of two.

Past RIT-µX activities revealed that a load simulator for the rf-generators would be helpful. A standardized load simulating the thruster is very useful during the RFG development. Furthermore it is an essential tool to establish a standardized rf-generator acceptance procedure. The development of an adequate load simulator is the second element of the MRGAN activity.

The focus of IEPC-2019-806 is the neutralizer. The development was primarily motivated by the missing performance of conventional thermionic devices for electron currents between some tenth mA up to few hundred mA. However, the RF-concept has also strong advantages in handling. The RIT-µX thruster itself is very robust against any pollution. However, both, thermionic and plasma bridge neutralizers are very sensitive against oxygen and humidity. Both can poison them irreversibly and special care is necessary for storage and handling. Getting the entire system insensitivity against environmental influences is clearly from benefit.

VI. Conclusion

Ariane Group and partners are developing a new neutralizer based on rf-ionisation instead of widely used thermionic electron emitters. The motivation for the development activity, which is embedded in the European Space Agency's Global study and Technology Program, was an identified shortcoming in performance with existing technologies in the range of some ten mA to few hundred mA.

The initial performance test and the preponed coupled test demonstrated that new RIT-µN neutralizer is capable to provide the required electron current for neutralization for four or more RIT-µX thrusters. The electron extraction is realized in plasma bridge mode. This ensures self- adjustment of neutralizer current to the ion current without need for any further control mechanisms. The first data show that the concept is also competitive with respect to power- and xenon consumption.

Analog to the main RIT-µX thruster also the RIT-µN neutralizer is non-sensitive against humidity and oxygen. This further easies handling and storage of RIT based systems.

RIT-µN Neutralizer	
Function Principle	RF Ionisation Plasma Bridge Electron Extraction
Dimensions	Lenght: Diameter:
Mass	400g
RF Power Consumption	<30W
Electron Current	> 120mA

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The support of the European Space Agency ESA for the reported activity is gratefully acknowledged.

References

[1] H.Leiter et al. "RIT-µX - High Precision Micro Ion Propulsion System Based on RF-Technology", 43rd AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Cincinnati, OH, July 8-11, 2007, No. AIAA-2007-5250

[2] D. Di Cara et al., Experimental Validation of RIT Micro-Propulsion Subsystem Performance at EPL ; IEPC-2013-90

[3] H. Leiter et al. RIT-µX Miniaturized Radio Frequency Ion Thruster Systems - Applications and recent Program Status, SPC-2018-00350

[4] RIT-µX - A New Advanced Miniaturized Ion Thruster System for Small Satellites, IAA Small Satellites Symposium, Berlin, 2011, IAA-B8-0904

[5] Hans Leiter, Christian Altmann, Ralf Kukies, Jan-Patrick Porst, Adaptation and Optimization of the RIT-µX Miniaturized Ion Propulsion System for Small Satellites, IAA Small Satellites Symposium, Berlin, 2015, IAA-B10-1101