Evolution of the AIRBUS DS GmbH Radio Frequency Ion Thruster Family

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Abstract: The Airbus DS Radio Frequency Ion Thruster "RIT" family and its evolution is presented. The first member of the family was RIT-10. Over the years the engine was carefully evolved. The recent RIT-10 EVO represents the state-of-the art in the 500W class. Taking benefit of the excellent scalability of the RIT technology the family grew in both directions and a thrust range from view micro Newtons to more than 200mN is covered. RIT-µX is the smallest engine for the low Milli- and Micro-Newton regime. In the 5kW class the RIT 2X series replaces RIT-22.

The basics of the radio-frequency ion thruster technology are provided. It is a flight proven technology: RIT-10 marked two milestones in the history of electric propulsion. Following a brief historical recall of the RIT-family the three thrusters RIT-µX, RIT-10 EVO and the RIT 2X series are presented together with their embedding systems.

I. Introduction

Electric propulsion (EP) has become state of the art for commercial geostationary satellites. More and more operators realize the advantages of EP for North South Station keeping and thanks to sufficient electric power on telecom platforms also electric orbit transfer will soon become standard.

The increasing electric power for satellite payload drives in parallel the development of electric propulsion towards higher thrust and power. This tendency motivated the development of the RIT-22 thruster and system. Offering more than 4,400s specific impulse makes RIT-22 also a good choice for scientific probes. Indeed, the RIT-22 development was strongly influenced by the needs of the European Space Agency ESA's scientific missions which differ from today's needs of telecom satellite operators. Here the performance profile is shifted slightly

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towards less specific impulse and more thrust. This trend is the origin for the evolutionary development of RIT-22 towards RIT 2X.

In the public perception EP is strongly linked with its high specific impulse and the related propellant mass saving. Clearly, high specific impulse represents the fundamental advantage of electric propulsion.

However, an appropriate EP technology offers features and advantages beyond simple mass saving. Especially the RIT provides perfect thrust control, in terms of resolution, response, reproducibility and linearity together with very low thrust noise. This is the key for new types of scientific missions. It enables in-situ compensation of atmospheric or solar drag and high precision formation flying.

A thruster for this type of applications is Airbus DS RIT-µX. It can be adapted to different thrust ranges in the low micro and milli Newton thrust regime. Thrust resolution better than a tenth of a micro Newton has been demonstrated. Onboard telecom satellites RIT-µX thrusters can serve as actuators for roll-control.

Thrust resolution, linearity etc. depends strongly on the performance of the power processing unit and highest performance has clearly its price. Relaxing the requirements for 'thrust quality' opens the door for less costly systems. Airbus provides a concept for the word of small satellites (75kg-300kg).

II. RIT Function Principle and System

A. Function Principle

Radio-frequency ion thrusters belong to the class of gridded ion engines. 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.

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

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 of two or three grids. Concentric holes in these grids form a large number of single extraction channels. Every of these channels represents 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.

Ionization and acceleration are clear separated processes. This allows tuning and adaptation of an existing thruster to changing performance requirements.

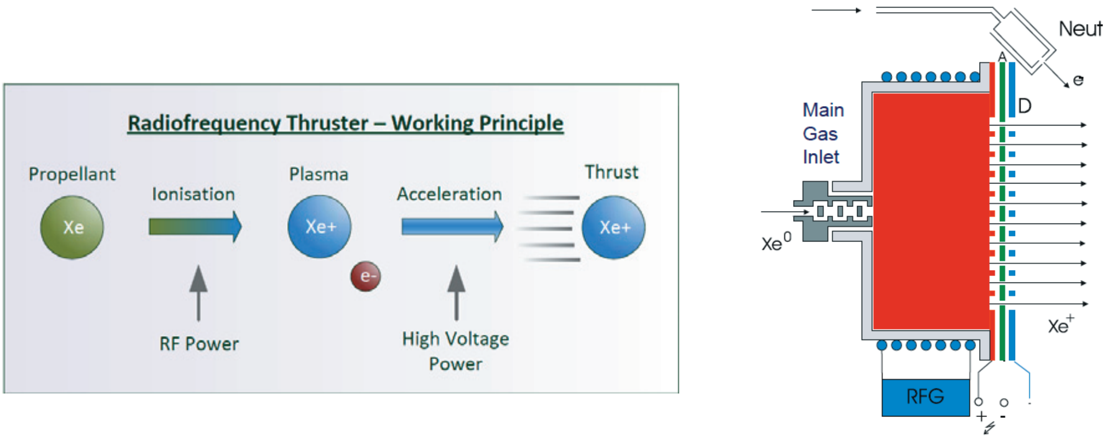

Figure 1 RIT Function Principle

Today, xenon is de-facto standard for all electrostatic thrusters (RIT, Kaufman, HEMP, HET) thus the RIT engines are optimized for the noble gas. However, the cathodless ionization allows operation with a manifold of propellants. Besides noble gases also inert and reactive gases can be ionized. For best performance ionizer and grid system have to be optimized accordingly.

B. RIT System Elements

The thrusters are embedded in a system. In the following the components for a RIT based EP System are summarized:

Neutraliser

A gridded ion thruster expels only positively charged ions. Necessarily the thruster's ion current has to be compensated with an equivalent electron current. Usually, hollow cathode type neutralizers are user for this purpose. Depending on the thrust range, for small thrusters, like RIT-µX, the propellant consumption of these devices is (too) high. Instead, gasless, low perveance e-gun type neutralizers are preferred Propellant

Management of the propellant flow

It is common practice to separate the propellant flow management into two steps: Pressure regulation and flow control. The pressure regulator reduces the high pressure inside the xenon storage, which might consist of multiple tanks, down to pressure of typically 2 bars. The constant pressure is fed to the flow control units ("FCU") for the individual thrusters. The FCU devices regulate the mass flow to each thruster.

Power Processing Unit

Besides xenon, the thruster needs one positive and one negative high voltage for the grid system and an alternating current for the thrusters ionization coil. The AC current through the coil is driven by a radio frequency generator ("RFG"). The RFG is con-trolled via a power processing unit (PPU). The PPU provides also the two high voltages for the thruster and the drivers for the FCU. In fact, the PPU has to provide all voltages required by the electric propulsion sub-system. The PPU interfaces with the power bus and the spacecraft's data bus. It receives high level commands and translates them into operation sequences. Also autonomous exception handling is implemented.

III. Milestones in Electric Propulsion

The radio-frequency technology is a flight proven: Two missions powered with Airbus DS' RIT-10 engines marked milestones in the history of electric propulsion

The RIT-10 engine was the first Western European ion thruster in space. It had its maiden flight onboard the retrievable platform EURECA (European Retrievable Carrier): EURECA was brought to space and back to Earth via SPACESHUTTLE. Most probably RIT-10 is the only ion engine that could be inspected after operation in space.

When RIT-10 was launched 1992 on EURECA people still complained about fundamental questions. Would the thruster deliver the predicted thrust also in space? Would neutralization work? Could there be unexpected events caused by electric propulsion?

The EURECA mission provided clear answers. The measured acceleration of EURECA confirmed the thrust prediction, obviously neutralization worked also fine and there were no unexpected interferences with the spacecraft. Especially, no feared influence on the tele-communication was observed. In overall, EURECA was an important step for a consolidated design of electric propulsion systems for future telecommunication satellites[1].

Shortly after the successful EURECA mission the work on an electric propulsion system for the European Space Agency's technology satellite ARTEMIS begun. Onboard the Advanced Relay TEchnogoy MIssion Satellite a system with two RIT-10 thrusters was installed for north south station keeping. A second system system built by DERA, now QinetiQ (GB) using two T5 ion thrusters was installed in parallel.

ARTEMIS became a further milestone in the history of electric propulsion. A failure in the upper stage of the launcher prevented the standard transfer of the satellite into the geostationary orbit. Using all the propellant for the chemical apogee thruster enabled the increase, and more important the circularization of the orbit. However, after the successful maneuver with the apogee engine there were still 6000km missing on the way to the geo orbit. It was part of the sophisticated maneuver strategy to cover this part of the journey by electric propulsion.

With its comparably small thrust of 15mN a RIT thruster was able to raise the orbit some 1000m per hour. After 6700 hour operation in total the job was done. ARTEMIS reached its destination[3]. It was the first electric orbit topping. ARTEMIS is still under operation[2].

Presently the discussion for future EP is much focused on "all electric". Indeed getting rid of the infrastructure for chemical propulsion onboard the satellite seems fairly attractive. However, ARTEMIS is an excellent example for *hybrid propulsion,* which means basically an optimized geo-transfer using both chemical and electric propulsion.

IV. RIT-µX

The presentation of the RIT-Thruster and system family starts with its smallest member: RIT-µX. The development was motivated by the needs of the European Space Agency's needs for their scientific missions, when in-situ compensation of atmospheric or solar drag and high precision maneuvering of spacecraft are required. The propulsion system must not introduce additional disturbing forces to the spacecraft. Low thrust noise is a further mandatory requirement.

A. Thruster, Projects and Achievements

When the RIT-µX development begun an extensive mission analysis was performed; Scope of the analysis was scientific missions. The analysis revealed three ranges of thrust from interest: 15-150µN, 50-500µN and 200-3000-µN.

In principle, for each thrust range a dedicated thruster could be designed, tested and finally qualified. At Gießen University, elegant breadboards of different ionizer size (1cm, 2cm, 2.5cm, 3.5 and 4 cm) were built and successfully tested [4,5].

The advantage of the 'size-and-thrust-dedicated' approach is a minimization of mass and power consumption. However, Airbus DS decided to realize a different approach. All thrust ranges shall be served with one standard thruster of same size equipped with adapted grid systems. Besides the evident economic advantages this approach ensures higher lifetime and, depending on the setting of the operation points, higher total efficiency and specific impulse. It is the inherent relation between thruster size and mass efficiency which is better for a larger engine.

At the time, the mission analysis was performed (2007), the most interesting thrust range was the one from 50-500µN. Consequently, the first elegant breadboard and the succeeding engineering model were equipped with an ion optics system for this medium thrust level. The IOS carries 37 extraction channels.

Meanwhile the full thrust spectrum is covered. In summer 2013 TRL5 was demonstrated for a RIT-µX System working in the thrust range 10-100µN. In this configuration RIT-µX is equipped with a 12 channel ion optics system. The demonstration included the verification of the challenging thrust quality requirements: Thrust linearity, resolution, response and noise are compliant with the requirements of ESA's LISA PATHFINDER mission [6]. In the same year TRL 5 was also demonstrated for thrust range 50-500µN.

The high thrust level was realized in 2015: In the light of upcoming ESA science missions there is the request for an extended thrust dynamic targeting 50-2500µN. The work on adequate ion optics began 2014. Meanwhile two IOS configurations, one with 61 channels and the other one with 121 have been successfully tested. For the 61 channel configuration a maximum thrust dynamic from 32 to 2500µN has been demonstrated and the 121 channel configuration war operated from 62-3200µN. A coupled system test for one of the configurations is scheduled for July 2015 succeeded by a 2,000h endurance test. Both test activities will take place in the electric propulsion laboratory of ESA's technology center ESTEC (Noordwijk, NL).

B. System Topologies

Figure 2 shows two principle system architectures. The PPU Centered Topology is the baseline for a RIT-µX system as under development for scientific missions. One PPU serves four RIT-µX thrusters with their RFGs and FCUs. For these spacecraft a 28V power bus and MIL 1553 bus for data transfer are common standard.

The PPU has to be designed also to comply with the thrust requirements. Thrust is produced in the RIT-µX engines, but the quality of thrust is mainly determined by the stability and precision of the supplied electric parameters which are generated inside the PPU.

The presented PPU Centered Topology for science missions will be equipped with one neutralizer per PPU. This approach minimizes the electric power consumption and maximum specific impulse is ensured because no additional xenon is required for its operation.

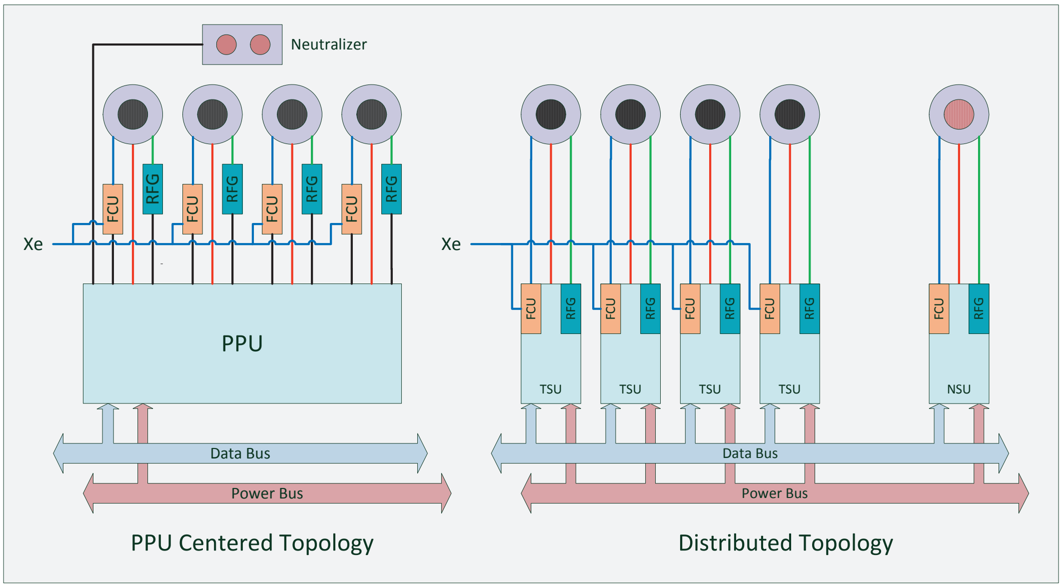

Figure 2 PPU Centered and Distributed Topology

The presented system topology is usable for different science missions. However, it is expected that the very specific requirements of each mission will require always a dedicated qualification program.

Outside the scope of scientific missions very different system needs apply. AIRBUS DS' discussions with customers revealed system configurations with a varying number of thrusters between 2 and 24.

Instead of designing and qualifying systems of the PPU centered topology according to each individual mission it appears more flexible to provide autonomous chains consisting of a thruster and a unit providing all the functionality required for its operation. Even the flow control unit can be accommodated inside a Thruster Supply Unit ('TSU') module. The distributed topology is depicted on the right of Figure 2.

The MIL 1553 bus is a very reliable, however costly approach. It is current baseline for RIT-µX 'Science Systems'.

Small spacecraft are often equipped with other bus systems, which can also provide better performance. The availability and application of these alternatives to MIL 1553 is essential for the distributed system architecture.

Also the neutralization is subject of AIRBUS DS' adaptation of RIT-µX systems for small satellites. The above discussed 'electron-gun type' devices rely on materials (as filaments or inserts) that are very sensitive against 'poisoning' caused by high humidity and reactive elements. Thus strict environmental and handling requirements have to be obtained.

These limitations triggered the development of a new type of neutralizers also derived from the radio-frequency ionization principle: A RIT-µX thruster that is optimized for extraction of electrons instead of ions.

The infrastructure for operation of a RIT-µX based neutralizer, its FCU, its RFG and the interface to the system will be provided by a Neutralizer Supply Unit ('NSU'). The NSU will be based on the TSU design. The main differences between NSU and TSU will be the high voltages for operation of the devices. It is the clear target to achieve the maximum commonalities between TSU and NSU.

V. RIT-10 and RIT-10 Evolution

The history of the RIT-10 thruster began in the seventies of the last millennium when Horst. W.Löb proposed the rf-ionisation for 'electrostatic' or 'gridded' ion thrusters [5]. He built several laboratory prototypes. Among them was a first thruster with a 10cm in diameter ionization chamber. It can be considered as the first RIT-10. In the German aerospace company MBB the potential of the new technology was realized and the development towards qualification of a commercial product was initiated. It was also the beginning of the long-term partnership between Gießen University and MBB which is today integrated in Airbus DS.

Tracking the history of RIT-10 is also a journey through the history of electric propulsion. The first RIT-10 used mercury as propellant. Together with cesium this was the standard in the pioneer years. The high atomic mass offered a good power to thrust ratio and it was easy to pump in vacuum facility. Cooling down with liquid nitrogen is sufficient to freeze out mercury. It was also possible to use a 'lake of mercury' inside the vacuum chamber as a beam target.

Despite its advantages the toxicity and reactiveness with (spacecraft) surfaces, especially solar array, makes mercury not a favorable propellant. Today it is fully replaced with the noble gas xenon.

The adaptation of RIT-10 from operation with mercury to the operation with xenon was the fist and most significant step in the evolution of RIT-10. Detail work and more available power increased the thrust continuously. The first prototypes and engineering models provided some 5mN thrust. During its maiden flight on EURECA the engine delivered 10mN thrust and 10 years later 15mN were achieved (ARTEMIS).

The most remarkable performance increase shows the RIT-10 EVO engine. Its design is identical to RIT-10 as qualified and flown on ARTEMIS excerpt the grid system. In RIT-10 EVO a contemporary grid design is implemented. With the new grid system RIT-10 is operable in an augmented thrust range 5-25mN (with peak performance 0.5-40mN).

During the last years the focus of interest of customers was not on RIT-10 EVO because its thrust was considered too small for current typical telecom platforms. Today, Airbus DS perceives a growing interest on RIT-10 EVO. The continuous increase of solar array efficiency provides more and more power also on smaller satellites (200-1000kg). For these smart platforms the thrust range of RIT-10 EVO together with its high specific impulse is attractive again.

VI. RIT-22 and RIT 2X

A. RIT-22

At the time ARTEMES demonstrated the capabilities of electric propulsion in orbit it was yet evident, that a thruster above of the RIT-10 class (Class of pioneer engines, electric power typically ~0.5KW) would be required to scope with future electric propulsion needs. Indeed, three years before ARTEMIS reached its geo orbit, Airbus DS had already launched the development of a radio-frequency engine in the 5kW class.

The breadboard of the 5KW thruster was called "RIT-XT". For the succeeding Engineering Model Airbus DS followed the convention labeling the electric thrusters indicating the ionizer size: RIT-22.

RIT-22 was tested extensively during comprehensive test programs. The thruster was endurance tested for 5,000 hours (continuous)[7], a 1000 hour cycled test was conducted, two RIT-22 engines were fired in parallel and the thrusters were exposed to challenging environmental load spectra.

Later the thruster interface (RIT-22 EM-2) was modified. It was made compatible to ESA's 'Electric Propulsion Pointing Mechanism - EPPM'. EPPM is compatible with 5kW class hall effect thrusters and QinetiQ's T6 ion engine. In a dedicated study compliance between RIT-22 and all requirements from EPPM was proven. In this study an evolutionary thruster design was anticipated (RIT-22 TMD).

RIT-XT RIT-22 EM RIT-22 EM-2 RIT-22 'TMD'

Figure 3 Evolution of the RIT-22 High Power Ion Thruster

B. RIT 2X Series

When the original RIT-22 development was initiated the focus was on highest specific impulse. Especially ESA's Mission BepiColompo required specific impulse above 4,500s. At the same time similar requirements were established for Alphasat, a new European 6t class telecom satellite in order to maximize communalities between development for commercial and institutional programs.

For science missions the need for highest specific impulse is still there and will remain. However, the request for orbit transfer/orbit topping shifts the focus for commercial satellites towards a lower power to thrust ratio to minimize transfer times in a given power budget. The change in the requested performance profile is reflected with the evolution from RIT-22 towards the RIT-2X thruster.

A further increase of available electric power onboard telecommunication platforms can be expected in the future. RIT-2X is designed to offers also the growth potential to utilize the additional power.

The first step from RIT-22 to RIT 2X was made with RIT-22 'TMD'. This thruster contains already new design features of RIT 2X, but it has still the same thruster size (cf. A. RIT-22). The thruster was test object of the 'Technology Maturity Demonstration' (TMD) campaign. TMD started in September 2013 and was completed in December. The campaign contained standard elements like performance mappings, a coupled test with new high voltage modules also designed and manufactured by Airbus DS[8] and a direct thrust measurement in the new German test facility operated by DLR Göttingen.

The results from the successful TMD campaign provide confidence that RIT 2X will meet the targeted performance data (Table 1). In addition the engine will provide a new high thrust mode with reduced specific impulse and up to 200mN thrust at less than 5kW input power.

The thruster design was completed June 2014. One year later the integration is completed. The first run-in and performance test of the engine is scheduled for July 2015. Figure 4 compares RIT-22 'TMD' and the new RIT 2X series thruster.

Figure 4 RIT-22 TMD and the new RIT 2X Series thruster

C. RIT 2X Systems and Building Blocks

The major element of a RIT 2X Subsystem is the thruster functional chain consisting of a RIT 2X Thruster, Neutraliser (NTR), Radiofrequency Generator (RFG), Flow Control Unit (FCU) and a Power Processing Unit (PPU).

This functional chain can be tested and delivered as an integral assembly and depending on the mission need, this functional chain can be duplicated up to the number of active and redundant thrusters needed.

The PPU is designed in a modular approach to allow implementation of several configurations: "non-redundant", "partially redundant" and "fully redundant". Today's demands consider thruster power between 4 and 5kW. However, the PPU design and thruster operational envelope allow for processing up to 6kW today. Thanks to the modular PPU approach and the high power capabilities of the thruster, this can be increased even further for future applications

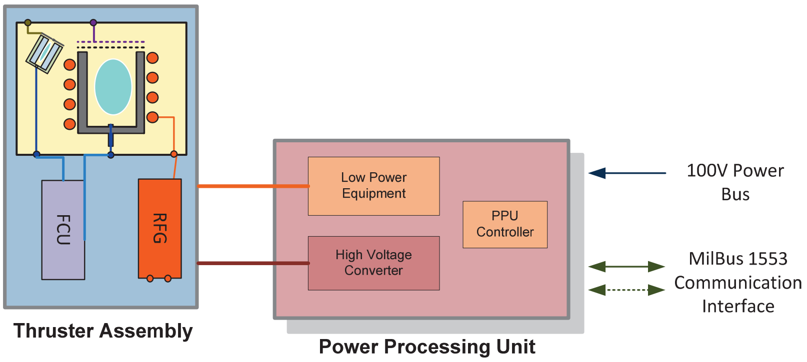

Figure 5 RIT 2X and Building Blocks

VII. Conclusion

The RIT Thruster family has been grown and evolved. Starting point and pioneer was the RIT-10 engine. The original engine was designed for operation with mercury. When mercury was no longer accepted by satellite operators the engine was adapted to the operation with xenon. Continuous product care improved the performance remarkably. Especially RIT 10 EVO demonstrates that the optimization of functional elements, in this case the thruster's grid system, can change the performance envelope significant.

The high scalability of the radio-frequency ion thruster technology is unique. Airbus DS worked in both directions. In the micro and milli-Newton regime RIT-µX offers thrust of highest *quality*. Thrust resolution, linearity, offset and thrust noise comply with the requirements of the most advanced scientific mission concepts.

On the other side of the spectrum Airbus DS presents the new RIT 2X Series thrusters. Derived from RIT-22 the engine is evolved towards today's demands of geo-satellite operators. To speed up orbit transfer also with gridded ion thruster technology a novella high thrust mode is implemented.

Table 1 summarizes key data of the Airbus DS' thruster family. As the RIT technology is operable in a broad family of characteristics the thruster's operational points can be tuned towards customer needs.

	Thruster		
	RIT µX	**RIT 10 EVO**	**RIT 2X**
Thrust & Power			
Nominal Thrust	50 - 500 µN	5mN - 15mN - 25mN	80mN - 115mN - 168mN - 200mN
nom. Power	< 50 W	145 W - 435W - 760W	2185W - 2985W - 4650W - 5785W
Functional Performance			
extended / on request	10-100µN, 300-3000 µN		
Isp	300 - 3000 s	> 1900s > 3000s > 3200 s	>3400s >3435 s >4000s >4300s
max. demonstrated	>3500 s	> 3400s	> 6000 s (RIT 22)
Divergance angle*	< 17°	< 15°	< 25°
Lifetime			
Total Impulse	>10kNs up to 200kNs	>1.1 MNs	>10 MNs
Max Operational cycles	>10000	>10000	>10000
Total Lifetime	>20000 h	>20000 h **	>20000 h
Technology			
Ionisation	RF-Principle	RF-Principle	RF-Principle
Acceleration	Electrostatic	Electrostatic	Electrostatic
Gridsystem	2 Grids	2 Grids	2 Grids
Propellant	Xenon	Xenon	Xenon
Design			
mass	440 g	1.8 kg	8.8 kg
Dimensions			
Diameter	78 mm	186 mm	308 mm
Length	76 mm	134 mm	215 mm
Environment			
Random	20-60Hz + 9db/octave 60-400Hz: 0.5g^2/Hz 400-2000Hz: -6dB/octave Overall: 18.4 gRMS	20-50 Hz: +6dB/oct 50-1200 Hz: 0.32g^2/Hz 1200-2000Hz: -6dB/oct Overall: 22.9gRMS	10Hz: 0.023 g^2/Hz 70Hz: 1 g^2/Hz 200Hz: 1 g^2/Hz 215Hz: 0.5 g^2/Hz 455Hz: 0.5 g^2/Hz 2000Hz: 0.026 g^2/Hz
Sine	5-20Hz 11mm (0-peak) 20-100Hz 20g	**Z-Axis:** 5-18 Hz 11mm 18-35 Hz 15g 35-60 Hz 12g 60-100 Hz 6g **X-Y-Axis:** 5-16.5 Hz 11mm 16.5-35 Hz: 12g 35-60 Hz: 8g 60-100 hz: 4g	5-33Hz: +- 10mm 33-100Hz: 38g
Shock	500Hz 100g 1000Hz 1500g 10000Hz 1500g	100 Hz: 10g 3000 Hz: 2000g 10000 Hz: 2000g	100 Hz: 10g 3000 Hz: 2000g 10000 Hz: 2000g
Operating Temperature	-40°C to +160°C	-75°C to + 140°C	-50°C to +190°C
Non-Operating Temperature range	-60°C to +160°C	-85°C to +140°C	-60°C to +190°C
Application			
NSSK	🟥☐☐☐	☐🟨🟩☐	☐☐🟩🟦
Primary Propulsion			☐☐☐🟦
Electric Orbit Raising	🟥☐☐☐	🟥🟨☐☐	☐☐🟩🟦
Ultra fine thrust control	🟥🟨🟩🟦		
* Half angle 95%			
Application	🟥 Small Satellites	🟨 Small Geo 🟩 Medium Geo	🟦 Heavy Geo

Table 1 RIT Family Thruster Data

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