Six Decades of Thrust - The Ariane Group Radiofrequency Ion Thrusters and Systems Family

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Abstract: The Ariane Group Radio Frequency Ion Thruster "RIT" family consists of three members: RIT-µX a miniaturized thruster systems for the Micro- and Milli-Newton thrust regime, RIT 10 EVO (5-25mN) a thruster derived from the flight proven RIT 10, and the new RIT 2X Series systems capable to deliver more than 200mN thrust per engine. In contrast to 'classic' gridded ion engines, RIT 2X provides an additional unique high thrust mode with slightly reduces specific impulse (2,500s) for an remarkably thrust to power ratio.

A general introduction in the basics of RIT thrusters and systems is given followed by the presentation of the three thruster systems and their specific applications. Finally, a brief description of production and test facilities completes the overview.

I. Introduction

For geostationary satellites the pioneer years of electric propulsion are gone. Electric propulsion (EP) is widely used for North-South-Station keeping (NSSK) and operators ask for adequate EP solutions for orbit transfer, too.

Performing both, NSSK and OR with one and the same engine introduces a challenge for the thruster design because the requirements for NSSK and Orbit Raising (OR) differ. During NSSK operation high specific impulse for maximum mass saving is highly desirable whereas OR requires higher thrust at cost of reduced specific impulse. It is the unavoidable trade in the triangle of power, specific impulse and thrust which results in a desirable specific impulse around 2,500s. Comparing the two major thruster technologies, Hall Effect Thrusters (HET) and Gridded Ion Engines (GIE) shows that the *natural best specific impulse* is typically ~800 s lower for HET and starts ~800s above for GIE.

Ariane Group faced this challenge and the result is the new RIT 2X thruster with its new and unique 2,500s high efficiency mode for high thrust maneuvers. This mode takes benefit of the special behavior of RIT engines, when operated with high RF-power and increased propellant mass flow.

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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 technology 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 or high precision formation flying. All these concepts are related with smaller spacecraft (50-300kg typ.)

A thruster for this type of applications is Ariane Group's RIT-µX. It can be adapted to different thrust ranges in the low micro and Millinewton thrust regime. Thrust resolution better than a tenth of a micro Newton has been demonstrated. Although the development of RIT-µX was clearly motivated by the needs of the European Space Agency ESA's ambiguous scientific missions, the field of applications is by far broader. RIT-µX systems can also power small commercial satellites. For earth observation and communication the satellites can be flown in substantially lower orbits; here, the EP system compensates the significant air drag in low altitude. This is the key to higher observation resolution or improved communication capabilities. Instead of circling around the earth, also small lunar or planetary orbiters can be considered, too.

A third field of application is from different nature: Onboard telecom satellites, RIT-µX thrusters can serve as actuators for roll-control.

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.

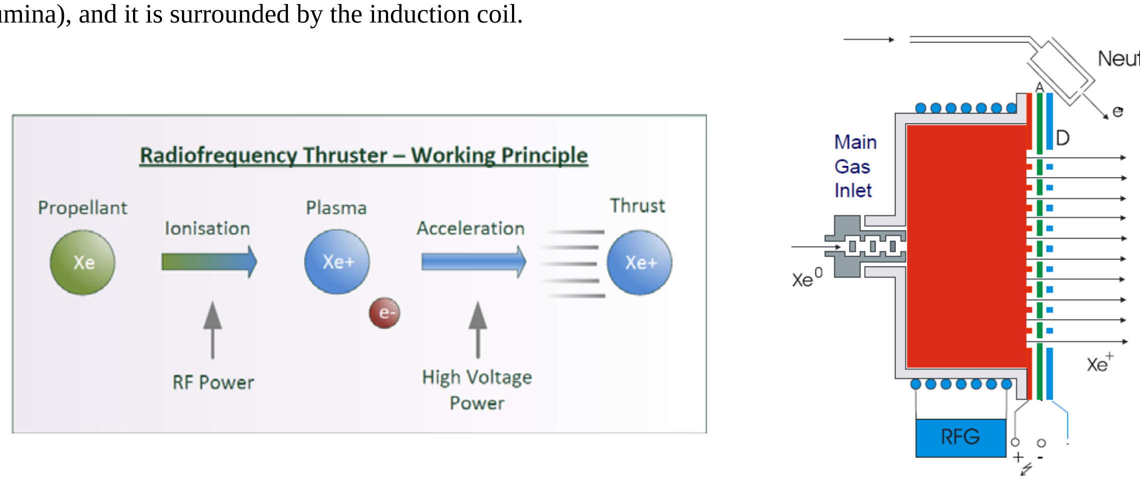

Figure 1 RIT Function Principle

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.

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 here.

Radiofrequency Generator (RFG)

The RFG converts DC current into the required AC current for the rf-coil inside the thruster. The ArianeGroup patented PLL technology ensures exact matching to the thruster's complex plasma impedance under all operational conditions.

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 Ariane Group' 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 with the US space shuttle ATLANTIS and back to Earth onboard the ENDEVOUR. 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 interferences between the electric propulsion system, its ion beam and its electron cloud on the one hand and the telecommunication systems and rf-waves on the other hand, were observed. In overall, EURECA was an important step with its proof of concept and 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 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. Thanks to RIT-10 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.

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, Ariane Group 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 the configuration with 61 channels was successfully performed and presently an endurance test is running in the electric propulsion laboratory of ESA's technology center ESTEC (Noordwijk, NL).

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 development targeting the 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 first 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, Ariane Group 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 becomes attractive again and a renaissance of RIT 10 sized engines is expected. Especially, for the market of 'mega constellations' the potential of a RIT 10 sized solution is rated very attractive by Ariane Group

VI. RIT 2X

A. RIT 2X Series Thruster

RIT 2X is Ariane Group's new 'flagship' RIT engine designed for the needs of contemporary and future telecommunication satellites. These satellites demand for dual mode operation. In NSSK mode high specific impulse is favorable (3,500 s and more) whereas the thrust level is from minor importance. Lower thrust can be compensated by higher firing time. For OR maneuvers the situation is different: Presently 'Time to Orbit' is the key requirement which can be accomplished only by sufficient thrust. Independent from technical realization and thruster type an electric engine's, power consumption is the product of thrust and exhaust velocity (divided by two times the total efficiency). Thus mission analysis has to trade specific impulse versus thrust. Outcome of spacecraft primes analysis is a specific impulse in the range of 2,500 s; this is ~ 800s above the typical Isp of HET and ~ 800s below the typical operational domain of gridded ion thrusters.

RIT 2X is the first gridded ion thruster offering a high thrust mode in this range of specific impulse. The challenge for gridded ion thrusters is the fact, that operating at lower Isp means operating at lower beam voltage. However, the required beam current for a given thrust increases which is opposite to the space charge limitation of any electrostatic ion thruster.

The implementation of the high thrust mode bases on four elements. First, there is the high beam flatness of RIT engines, which provides a homogenous load to the thruster's grid system. Beam profile measurements performed in the near field of the engines confirmed, that a high xenon throughput further increases the flatness.

Second, there is the composition of the grid system. From the very beginning, Ariane Group is using graphite for the acceleration grid instead of commonly used molybdenum. The sputter yield of graphite is typically 6 times lower than the one of molybdenum.

Third element is the plasma properties of rf-discharges. At any power level an increase of xenon throughput reduces the electron temperature. In fact, the RIT 2X electron temperature is lowest in the high thrust mode and screen grid erosion is nt an issue in the mode.

Forth, accomplishing the required beam current made a slight increase in size necessary. The inner diameter of the RIT 2X ionizer is 6cm larger than the one of RIT-22. More information about RIT-22, its test heritage and its evolution is provided in Ref. 9.

In the next years a further increase of electric power onboard geo-satellites can be expected. This will also shift the trade between Isp and thrust more towards specific impulse. Thus, RIT 2X contains also a third mode for high Isp and high thrust. This mode is already supported by the PPU which is ready to process up to 6.5kW input power.

Figure 2 RIT 2X thruster firing (left) and RIT 2X thruster at the shaker (right)

B. 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 6,5 kW today. Thanks to the modular PPU approach and the high power capabilities of the thruster, this can be increased even further for future applications

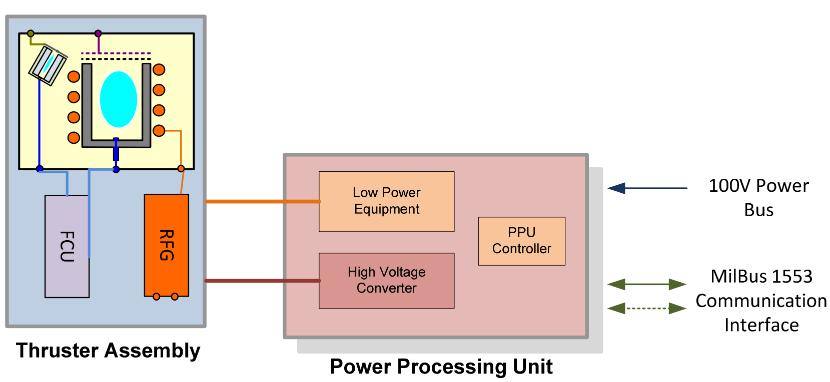

Figure 3 RIT 2X and Building Blocks

C. RIT 2X Systems - Manufacturing, Integration, Assembly and Test

The primary, functional design, of RIT 2X bases on the electric propulsion heritage and experience gained with RIT 10 EVO, RIT-µX and the predecessor engines of RIT 2X the RIT-XT and RIT-22 engines. For the final manufacturing compatible design, the Ariane Group experience in orbital propulsion with chemical thrusters and systems is the second essential element.

RIT 2X Thruster production and system tests will be performed at Ariane Group Site 'Lampoldshausen'. Here, more than 3,000 10N hydrazine thrusters have been manufactured and up to now more than 120 bi-propellant and 140 mono propellant systems have been assembled.

In 2006 a new integrated manufacturing center was built. All fundamental steps of manufacturing and integration are performed within one building only. Also all necessary cold tests and the mechanical tests (vibration/shaker) are conducted inside.

From the very beginning Lampoldshausen site has all facilities for hot firing of chemical thrusters and in fact, the need for testing chemical thrusters was the major origin for establishing Lampoldshausen operated by the German Space Agency DLR and Ariane Group. For chemical propulsion test stands covering the needs from 1N chemical, hydrazine, up to the Ariane Vulcain engines (LOX, 1359kN thrust) are available. Since 2017 also a test facility for EP is available on site. The vacuum chamber (3m Diameter x 6m length) contains beam diagnostics and all the required equipment for thermal cycling.

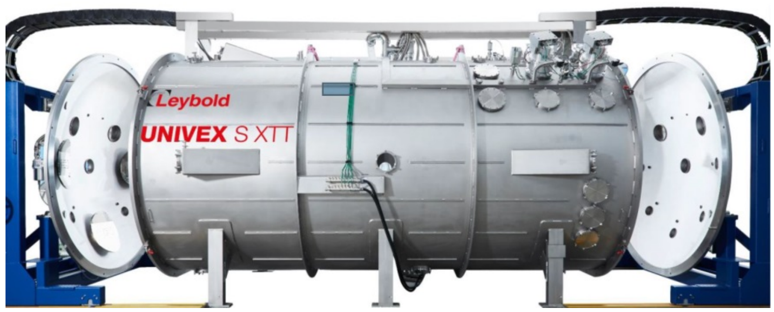

Figure 4 Ariane Group "M69" Integrated Manufacturing Center (left) and Electric Propulsion Acceptance Test Facility AsteriX (right)

VII. Conclusion

The Ariane Group RIT thruster systems family covers a thrust range from micro-Newton to Newton, in overall 6 decades of thrust. Smallest member of thrusters is the versatile RIT-µX engine. Powered with by a high precision PPU it offers thrust resolution better than a tenth of a micro-Newton. This outstanding precision, key to ambiguous scientific missions, is not always required. Operated with a simplified PPU or a dedicated "Thruster Supply Module", a RIT-µX system represents an attractive propulsion system for small satellites in low earth orbits. Other applications are primary propulsion for small lunar or planetary orbiters. Even using RIT-µX as an actuator device for geo-satellites can be considered.

Origin of all developments was the RIT-10 thruster. Writing chapters in the history of space propulsion, the engine was basis for the successful down- and upscaling of the technology. In the last two decades the interest of 0.5 kW-0.9 kW thrusters was decreasing. New concepts for spacecraft and mission might trigger a renaissance of this engine class. RIT-10 EVO with a thrust range 5-25mN (0.5-40 peek) is available for these needs.

Newest member of the RIT systems family is RIT 2X. Together with its PPU, RIT 2X is the first multi-mode gridded ion thruster by Ariane Group. For NSSK maneuvers the system operates in 'classic' high specific impulse mode (Isp > 3,500s; F 80-120mN). For OR the engine is operated at reduced specific impulse (2,500s) for a good specific thrust to power ratio. Thruster and PPU are both designed to process up to 6,5kW power. For the next evolution in available power onboard geo-satellites, RIT 2X systems are designed also for high thrust high specific impulse operation.

Ariane Group brings in also its heritage and experience from chemical propulsion. The facilities of Ariane Group's site Lampoldshausen are optimized for serial production of thrusters and systems. A new test facility for electric propulsion completes the manufacturing chain.

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	RIT µX	RIT 10 EVO	RIT 2X
THRUST & POWER			
Nominal Thrust nom. Power	50 - 500 µN < 50 W	5 mN | 15 mN | 25 mN 145 W | 435 W | 760 W	80 mN | 160 mN | 180 mN | 205 mN 2300 W | 4300 W | 4300 W | 5000 W
FUNCTIONAL PERFORMANCE			
extended / on request Isp max. demonstrated Divergance angle*	10-100 µN, 300 - 3000 µN 300 - 3000s > 3500s < 17°	> 1900s | > 3000s | > 3200s > 3400s < 15°	> 3800s | > 3400s | > 2700s | > 2800s > 6000s (RIT 22) < 25°
LIFETIME			
Total Impulse Max Operational cycles Total Lifetime	> 10kNs up to 200kNs > 10000 > 20000 h	> 1.1 MNs > 10000 > 20000 h	> 10 MNs > 10000 > 20000 h
TECHNOLOGY			
Ionisation Acceleration Gridsystem Propellant	RF-Principle Electrostatic 2 Grids Xenon	RF-Principle Electrostatic 2 Grids Xenon	RF-Principle Electrostatic 2 Grids Xenon
DESIGN			
mass Dimensions Diameter Height	440 g 78 mm 76 mm	1.8 kg 186 mm 134 mm	< 10 kg < 330 mm < 220 mm
ENVIRONMENT			
Random	20-60Hz: +9db/oct 60-400Hz: 0.5g^2/Hz 400-2000Hz: -6dB/oct Overall: 18.4gRMS	20-50Hz: +6dB/oct 50-1200Hz: 0.32g^2/Hz 1200-2000Hz: -6dB/oct Overall: 22.9gRMS	20Hz: 0.004g^2/Hz 100-250Hz: 0.1g^2/Hz 400-800Hz: 0.4g^2/Hz 2000Hz: 0.006g^2/Hz Overall: 8.1gRMS
Sine	5-20Hz: 11mm (0-peak) 20-100Hz: 20g	Z-Axis: 5-18Hz: 11mm 18-35Hz: 15g 35-60Hz: 12g 60-100Hz: 6g X-Y-Axis: 5-16.5Hz: 11mm 16.5-35Hz: 12g 35-60Hz: 8g 60-100Hz: 4g	5-20Hz: +- 10mm 20-100Hz: 35g
Shock	500Hz: 100g 1000Hz: 1500g 10000Hz: 1500g	100Hz: 10g 3000Hz: 2000g 10000Hz: 2000g	100Hz: 10g 4500Hz: 10000g 10000Hz: 10000g
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

Table 1 RIT Family Thruster Data