RITA Ion Propulsion Systems for Commercial and Scientific Applications

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Propulsion systems based on gridded ion thrusters are the technology that allows substantial performance improvements for commercial and scientific satellites. Thanks to their high specific impulse capabilities, the systems offer mass savings by reduced propellant consumption on station keeping applications for telecommunication satellites or deep space science missions. Astrium can offer ion propulsion systems for medium and large satellites for powers between 500 W and 6 kW in the thrust range between 10 mN and 175 mN at specific impulses from 3000 s to 4800 s. Based on the flight heritage of the RITA-10 system on ARTEMIS a high power system based on the RIT-22 is under development and has already completed 5000 hours of life testing on the thruster. This high power system can be used for the next generation telecommunication satellites, the needs of future science missions such as ESA's BepiColombo mission to planet Mercury and the orbit rising of large LEO structures. The core component, the thruster RIT-22 is under development by Astrium GmbH. In contrast to other ion engines developed worldwide, the Radiofrequency Ion Thrusters (RIT) have an unique feature: The propellant is ionized cathodeless by electromagnetic waves. This, so called "Radio Frequency Ionisation", guaranties for highest reliability (no life limited cathode inside, intrinsic isolation from the discharge plasma on high voltage potential to the surroundings) and flexibility in design. The characterization includes the basic performance mapping, extended beam diagnostics and direct thrust measurement. Also tasks, as dual operation of two thrusters in the vacuum test facility to study possible interactions between the engines and the operation under high solar thermal radiation environment have been performed. Principally, the rf-technology shows the inherent advantages also under this extreme environment. The avoidance of any cathode inside the thruster which has to be adapted to the high temperatures in its surroundings is a clear advantage.

To complete the bandwidth an ASTRIUM led team has started the development of small RIT engines capable to operate in the low mN to µN range. The performances and targeted applications for the different thrusters will be addressed. Tests dedicated to specific missions will be explained. A brief technical description of the engine together with an explanation of the radio-frequency principle, the system description and the thruster's heritage will complete this paper.

I. Description of Technology

Thrust generation in gridded ion thrusters is a process consisting of two steps. The thrust itself is generated by acceleration of electrically charged propellant particles in static electric fields. Therefore it is necessary to ionize the propellant in the step before.

Radio Frequency Ion thrusters (“RF” – Thrusters”) are operated without any hot cathode (“main cathode”) inside the thruster's ionization unit. Instead, the propellant is ionized by electromagnetic fields. For that, the ionizer chamber, a vessel made of an isolating material, is surrounded by an rf-coil. The coil induces an axial magnetic field. Finally, the primary magnetic field induces by Maxwell's Law a secondary circular electric field in which free electrons gain the energy for impact ionization.

After any impact ionization a xenon ion and at least one more free electron is gained. Once the ionization process is triggered, a self-sustaining plasma-discharge is formed. The employed frequency is typically in the range of one megacycle.

It is important to point out that this type of discharge and the physics behind (thruster respectively) are totally different from ECR-thrusters operated with some giga-cycles. The later ones require external static magnetic fields to establish an electron cyclotron resonance. Therefore the propellant flow through an ECR-type thruster has to be matched exactly to the resonance conditions. These are determined by the frequency of the electromagnetic waves together with the field strength of the static magnetic field.

Such limitations do not apply for RIT-Engines: The mass flow can be varied over an extremely wide range. This makes the rf-ion thruster superior, if fast changes of thrust level are necessary. The desired thrust is reachable faster than milliseconds by simply changing the applied rf-power.

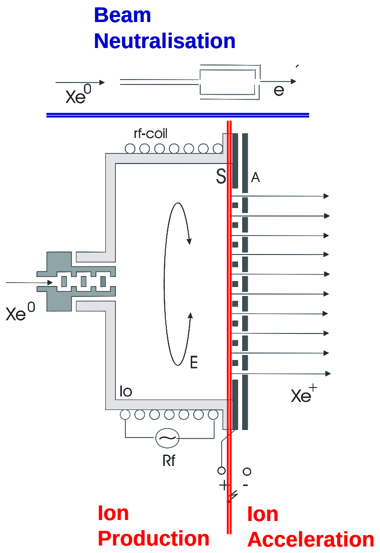

Figure 1 RIT Operation Principle

Beam current and with that the thrust follows the rf-power immediately. It is absolutely sufficient to adapt the mass flow within the given speed of the xenon flow control unit. Merely the specific impulse varies until the mass flow reaches its optimal value again.

Although the way the propellant is ionized is totally different from Kaufman- or more generally spoken from “bombardment thruster” and ECR systems, there is no difference in beam forming and acceleration between these different types. Sets of at least two grids are used to extract the ions from the plasma and after that to accelerate them.

Usually, a positive voltage in respect to satellites potential U+ is applied at the plasma sided grid and a negative voltage at the following one. The negative voltage U- at the second “accelerator” grid prevents a back streaming of electrons from the downstream surroundings of the thruster into the discharge area and allows a higher voltage for ion extraction (U+ + | U-|) than for the beam acceleration (U+) only.

Sometimes a third grid on nearly satellite ground is used to prevent back streaming charge exchange ions generated in the downstream region of the ion beam hitting the acceleration grid. Also this third grid has an influence on the beam’s shape. The specific advantages and disadvantages of triple and double grid systems often discussed for bombardment-type engines apply for radio-frequency ion thrusters as well. Like all type of electrostatic ion engines, RIT thrusters need a device for neutralization of the generated ion beam too. For that, commercially available hollow cathodes are used as electron emitters.

Figure 2 shows a view in to a RIT-22 thruster recently under development. As can be seen, only a very few functional components are needed. Especially it should be noted that the discharge vessel is empty, e.g. no main cathode is needed. In addition the discharge vessel is made of isolating alumina, which is not subject to erosion by the plasma particles. By this is gets obvious that in a RIT thruster only the acceleration grid is subject to erosion.

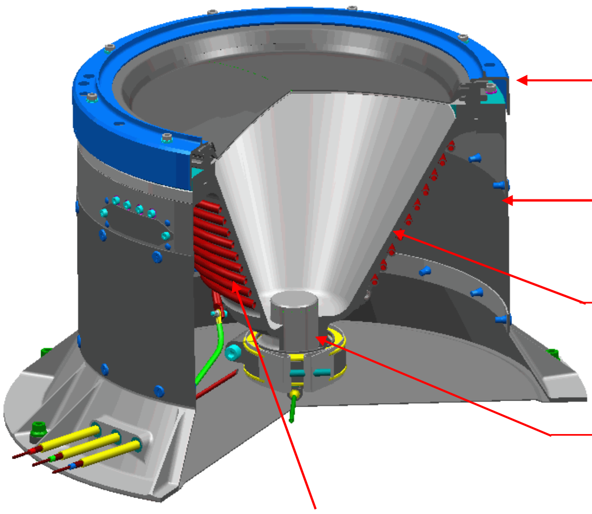

Figure 2 RIT-22 explanation of components by means of 3D model)

However the thruster is worth nothing without the power and propellant supply. Figure 3 show a block diagram describing the RITA system.

II. Heritage

The research on ion thrusters started at the 1st Institute of Physics, Giessen University, in 1962, when the idea of an rf-ionization of the propellant (Hg) was born.1 First of all, the fundamental processes were studied, and an engine with a 10 cm ionizer diameter, called RIT-10, has been investigated and optimized. [1]

This standard thruster reached the stage of a laboratory prototype in 19703, when the MBB company (later Dasa, now EADFS-ST) started its industrialisation and qualification procedure, culminating in the EURECA space test (1992) and the ARTEMIS mission (2002).

Besides RIT-10, an rf-thruster family with ionizer diameters from 2 cm to 35 cm has been designed, built, investigated, and tested at Giessen University.

One of the research focuses of the EP-team has been the plasma and beam diagnostics. Also some thruster components like the neutralizer and the vaporizer/isolator-system have been investigated. Thruster spin-offs for fusion plasma heating and for material processing have been developed, built, and tested at Giessen, too.

To model an ion thruster means to clear up all physical processes inside the ionizer and the beam formation system, which are relevant for the thruster operation, and to lay down a complete theoretical description. This procedure must include both the stationary, equilibrium effects like the energy or the ion balance (being important for stand-by and thrusting operation) and also the non-stationary events, e.g. during ignition of the discharge or in the case of arcs between the grids.

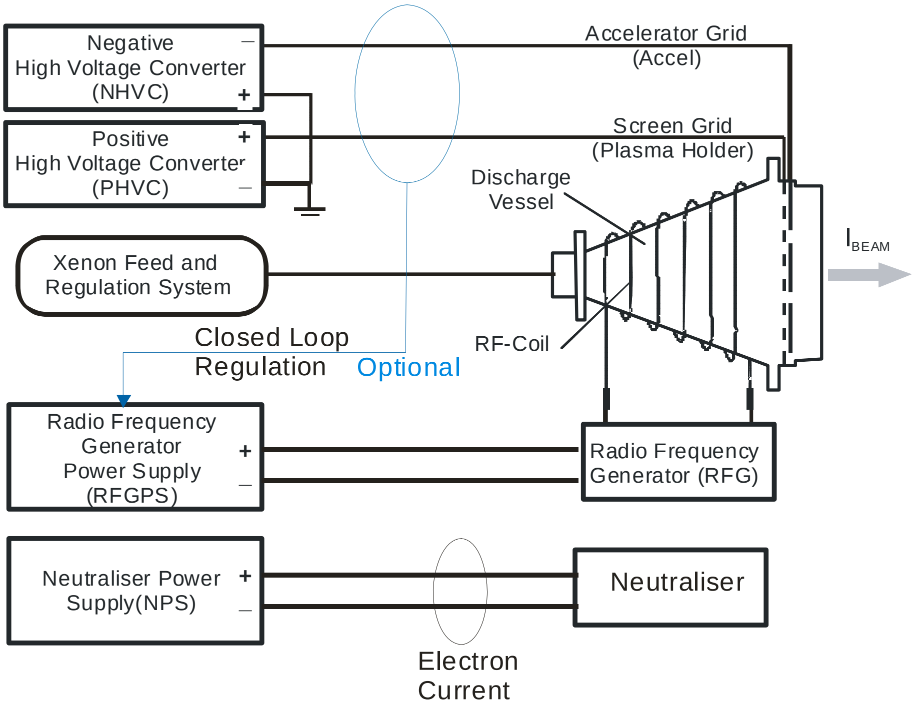

Figure 3 RITA System Block Diagram

Since 1970 it was the intention of ASTRIUM-ST (previous MBB) to develop ion thrusters for application in space. Using basic ideas and development work performed by Prof. H.W. Loeb and its group at the University of Giessen a number of RF-Ion Thrusters RIT have been developed in close co-operation between the industry and an Institute of the University.

Contributions from the University were basic plasma physics, basic operation of ion thrusters and neutralisers and performance of development and function tests in a dedicated test facility. Engineering tasks, like design, manufacturing and subsystem preparation have been contributed by the industry. The different models built and flown by ASTRIUM ST are shown in Figure 4.

A first possibility for a test of the RIT 10 thruster came up as an experiment on the EUropean REtrievable CArrier EURECA. As one of the 16 experiments on this platform RITA (RIT Assembly) should be able to be operated for more than 1000 h in the orbit of about 500 km during the one year mission time.

According to the power level available for RITA the thruster has been operated in space for about 240 hours at thrust levels between 5 and 10 mN. After that time a soldered wire connection at the inlet of the RF-coil broke by overheating due to a mixture of the solder- and copper material of the coil, which resulted in a decreasing conductivity of the new alloy. The retrieval of the EURECA platform with all the experiments to earth by the space shuttle gave us the possibility to investigate the failure in detail. The failure can easily be avoided by welding of this connection instead of soldering.

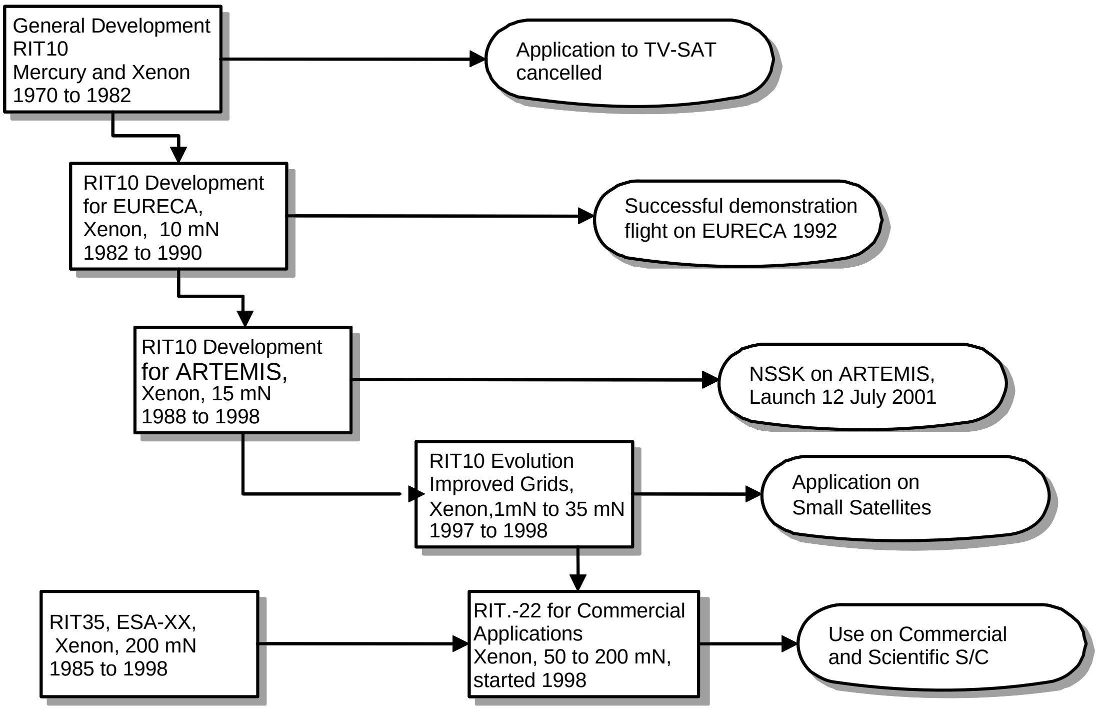

Figure 4 Development Steps of the RIT Thruster.

III. The RIT-10 based propulsion system

The 2nd flight of a European ion propulsion system was onboard Artemis, an experimental communication satellite.

The satellite is equipped with 4 ion thrusters including the necessary electronics and flow controllers to perform North-South station keeping as a responsible subsystem for the total satellite lifetime of 10 years. 2 thrusters UK 10 from Astrium UK and 2 RITA from ASTRIUM-ST are mounted on 2 gimballed platforms.

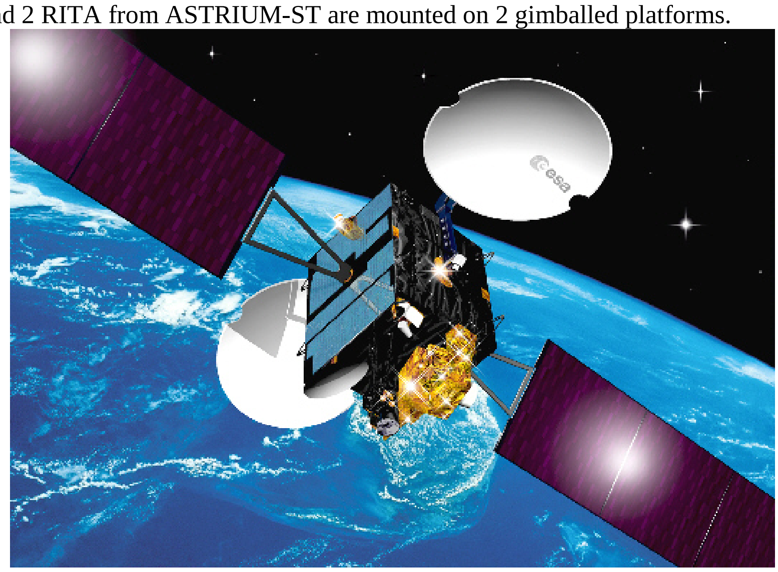

Figure 5: Ion Propulsion Package on Artemis

For this application the thrust level of the RIT thrust level was increased to 15 mN at a specific impulse of > 3000 s. The lifetime requirement is around 10.000 h at an operation time of about 3 h per day during the mission time of 10 years. [2]. The challenge of this development was the increase of the thrust level of RIT from 10 to 15 mN under the consideration of a lifetime capability of 15,000 h, which include a qualification factor of 1.5.

The Ion Propulsion Package (IPP) for ARTEMIS **Fehler! Verweisquelle konnte nicht gefunden werden.**; **Fehler! Verweisquelle konnte nicht gefunden werden.**, was developed under the leadership of Astrium GmbH, to provide the Δv required for North-South-Station-Keeping. For this purpose as shown in Figure 6 one couple of thrusters, consisting of one RIT (Radiofrequency Ion Thruster) and one EIT (Electron-bombardment Ion Thruster), is mounted on an alignment mechanism (ITAM – Ion Thruster Alignment Mechanism) on the north- and on the south panel.

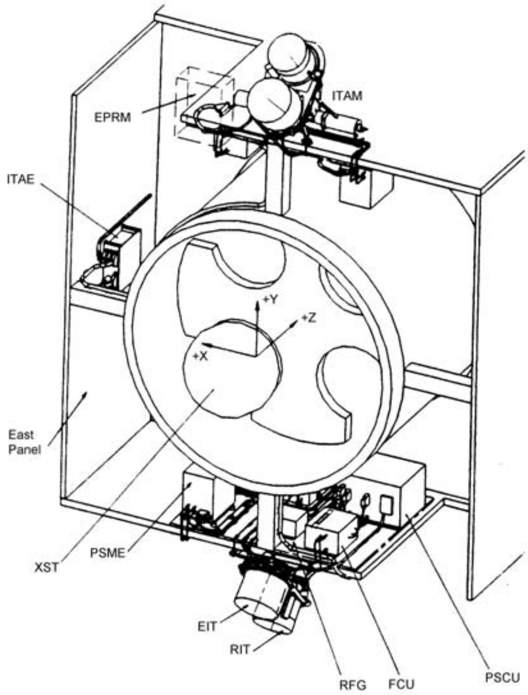

Figure 6: Allocation of IPP on ARTEMIS

To avoid that the fast ions of the beam impinge on the solar cells the thrusters are oriented canted away from the solar arrays as shown in Figure 7. Both EIT and RIT thrusters have very low beam divergence angles, minimising any possibility of interactions with the solar arrays.

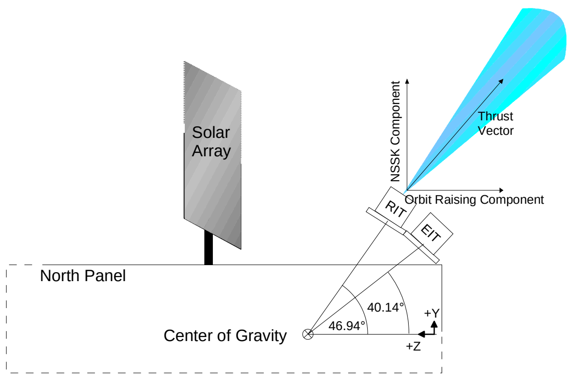

Figure 7: Ion Thruster Orientation ARTEMIS

For NSSK (inclination control) one thruster on the north panel will be operated for 3 hours when the satellite passes the ascending node and one on the south panel 12 hours later, when the descending node is passed. The complete IPP consists of the following assemblies:

- 1 Propellant Storage and Distribution Assembly (PSDA) [Astrium Ltd] including the Xenon Storage Tank (XST) [MAN-Dowty], the Electronic Pressure Regulator Mechanism (EPRM), the Electric Pressure Regulator Electronics EPRE which is physically included in the EITA electronic box, and high and low pressure Fill and Drain Valves (FDV) [Raufoss].
- 2 Electron Bombardment Ion Thruster Assemblies (EITA - Kaufman type), [Astrium Ltd.]. The EITA subassemblies are the thruster EIT, the Propulsion Control and Electronics PCCE, and the Propellant Supply and Monitoring Equipment (PSME). Further details are given in [11] and [12].
- 2 Radiofrequency Ion Thruster Assemblies (RITA) [Astrium GmbH]. The RITA subassemblies are the thruster ERT, the Power Supply and Control Unit PSCU, the Radio Frequency Generator RFG, and the Flow Control Unit (FCU). A detailed description of the RITA is given in **Fehler! Verweisquelle konnte nicht gefunden werden.** to **Fehler! Verweisquelle konnte nicht gefunden werden.**.
- 1 Ion Thruster Alignment Assembly, consisting of- 2 Ion Thruster Alignment Mechanisms (ITAM) [Austrian Aerospace] and the Ion Thruster Alignment Electronics (ITAE) [Astrium GmbH], which has a pointing range of > 6° half-cone angle from the nominal orientation.

Figure 8 shows the block diagram of the IPP assemblies. The solid lines demonstrate the Xenon feed line tubes, while the dotted lines represent electrical connections.

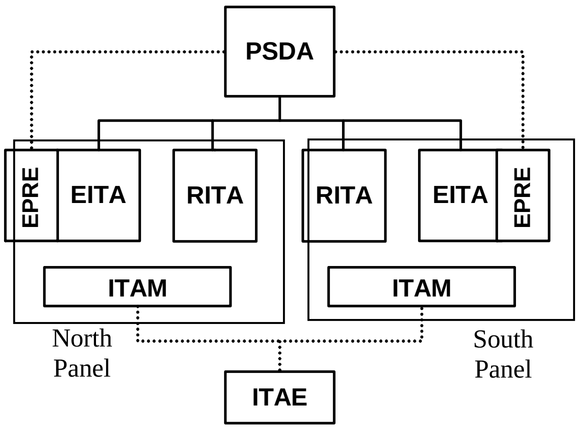

Figure 8: ARTEMIS IPP block diagram

The flight hardware of the electric propulsion package has been delivered for integration into the spacecraft in 1998. At the same time a lifetime test on the EQM thruster and neutraliser has been started to demonstrate the overall lifetime. The test was performed in the Gigant test facility at ESTEC in Noordwijk, Holland, and it was terminated after successful 20.000 hours of operation which is twice the mission requirement. The additional 5000 hors of operation that exceeded the original life test requirement was performed to support the flight operations.

Due to a launcher failure of the Ariane 5 the satellite was injected into a too low elliptic orbit. Chemical thrusters have been used to increase the orbit to 31,000 km circular. The ion thrusters, originally planned to be used for North/South station keeping only, finally was to only chance to transport the satellite to its geosynchronous orbit.

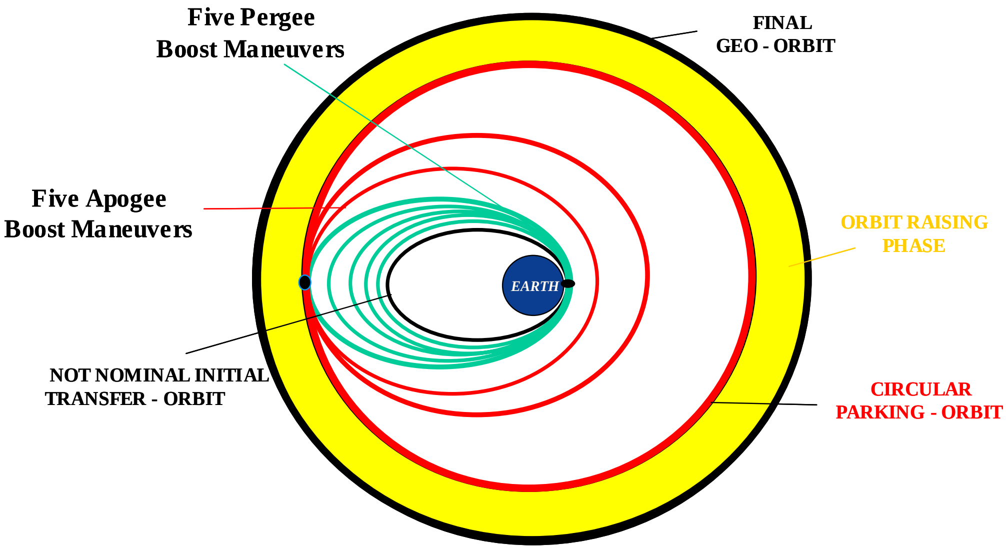

Figure 9 Manoeuvre Strategy for ARTEMIS Salvage Mission

The final orbit raising to geostationary altitude is being performed by means of the ion propulsion system (IPP) applied in a newly designed spacecraft attitude control mode [9]. Thales-Alenia-Space Italy and Astrium, in close cooperation, quickly redesigned all control and data handling software modules affected since the original spacecraft configuration was designed for inclination control only and not to generate thrust with the ion engines in a direction tangential to the orbit.

Finally the 2 RITA assemblies delivered more than 90% of the total Δv to be delivered by the IPP. Especially RITA2 demonstrate the life time needed for a 6 year station keeping mission. [9]

	RITA1	RITA2	EITA1	EITA2
Total On-Time	**1140.6 h**	**6427.2 h**	**182.3 h**	**521.0 h**
Total Mass	**2.14 kg**	**12.06 kg**	**0.49 kg**	**1.40 kg**

The flexibility of the IPP system consisting of 4 thruster assemblies including the 2 alignment mechanisms for precision thrust direction control, had proven invaluable.

A RIT as designed and qualified for Artemis was equipped with a grid system optimised for maximum thrust level. The purpose of this thruster was to increase the performance at reduced power demand. This thruster completed 2300 hours of system life test and is capable for station keeping, drag compensation and orbit maintenance of medium size satellites. In addition the EVO was a subscale model to demonstrate the performance features of the large RIT-22 thruster.

IV. Developments of the RIT-22 based system

Currently Astrium is developing a thruster called RIT-22 for large commercial satellites and for primary propulsion of deep space missions like ESA's Bepi Colombo. [3], [4]; [5]

An initial development model named RIT-XT was build and successfully operated in a 1000h / 1000 cycle test as well as during numerous performance characterisations. The characterization includes the basic performance mapping, extended beam diagnostics and direct thrust measurement. Also tasks, as dual operation of two thrusters in the vacuum test facility to study possible interactions between the engines have been performed.

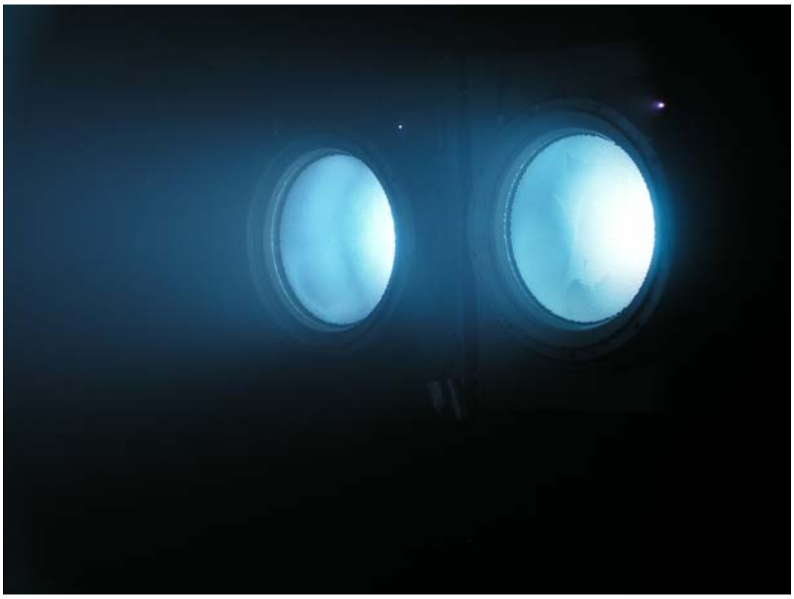

Figure 10 RIT-22 during simultaneous operation of two thrusters

This test was very valuable to check whether such an operation scheme using multiple thrusters can be used e.g. for deep space missions or orbit raising of geosynchronous satellites. For this test both thrusters were operated at thrust levels between 100 mN and 200 mN at identical or different thrust levels. In addition t e operation of two thrusters using one neutraliser only was tested. This was not new, as onboard of ARTEMIS two RITs have been operated simultaneously. But those were several meters apart and no beam diagnostics was available. Therefore in this test special emphasis was put on distance effects from closest distance, both thrusters nearly touching each other to the maximum distance of 0.7 m that could be achieved in the test chamber. A typical clustering distance of thruster will be somewhere between these two distances. [7]

Of course, the design goal, a specific impulse of more than 4000s for the basic, but most important commercial application, the north-south-station keeping of geo synchronous could be successfully demonstrated early. For north-south station keeping, the nominal thrust is set to 150mN. The thrust range reaches from 25mN up to more than 250mN. The dynamic of more than 1:10 is correlated with an increasing specific impulse with raising thrust. In fact, a maximum specific impulse of more than 6000s could be successfully demonstrated in 2003.

Based on the DM, which were built to allow an easy variation of the components, the final design of the RIT-22 was performed. The design chosen for the DM was already as good that all functional parts like grid system, gas feeder and RF-coil could be kept unchanged. Only the structure was to be adapted for the new I/F requirements and the launch environment. 2 EMs were built and are currently being tested.

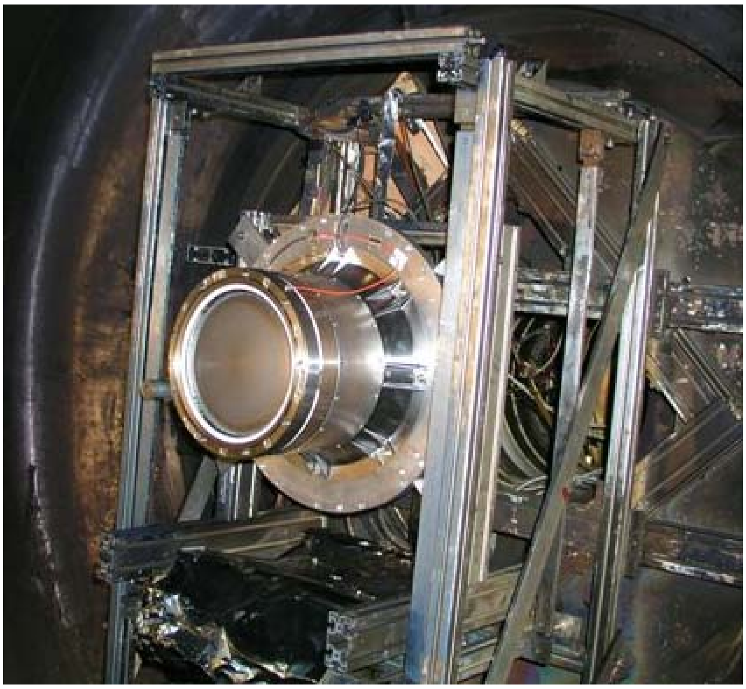

Figure 11 RIT-22 EM installed in thrust measurement device

Considering interplanetary missions, ESA's corner stone mission BepiColombo, a journey to Venus including an orbiter and lander to the suns nearest planet is one of the most ambiguous challenges for electric propulsion and space engineering in the near future. Especially the extremely high thermal environment forces spacecraft design "on the limit".

Principally, the rf-technology shows the inherent advantages also under this extreme environment. The absent of any cathode inside the thruster which has to be adapted to the high temperatures in its surroundings is a clear advantage. Nevertheless the thermal load for the grid system is extremely high. In the framework of an ESA activity called "New Grid systems for Ion Engines" ASTRIUM ST started the design and manufacturing of a grid optimized for the BepiColombo mission. The technology readiness will be demonstration is ongoing.

Currently one of the RIT-22 thrusters has completed a 5500 hour life test at a thrust levels of 175 mN and 150 mN at a specific impulse greater 4800 s. This proves the maturity of the thruster and the RITA system.

XST	Xenon Storage Tank
XFI	Xenon Filter
XRA	Xenon Regulation Assembly
FDV	Fill and Drain Valve
PPU	Power Processing Unit
TSU	Thruster Switching Unit
RFG	Radio Frequency Generator
FCU	Flow Control Unit
RIT	Radiofrequency Ion Thruster
GAM	Gimbal Assembly Mechanism
GAE	Gimbal Assembly Electronics

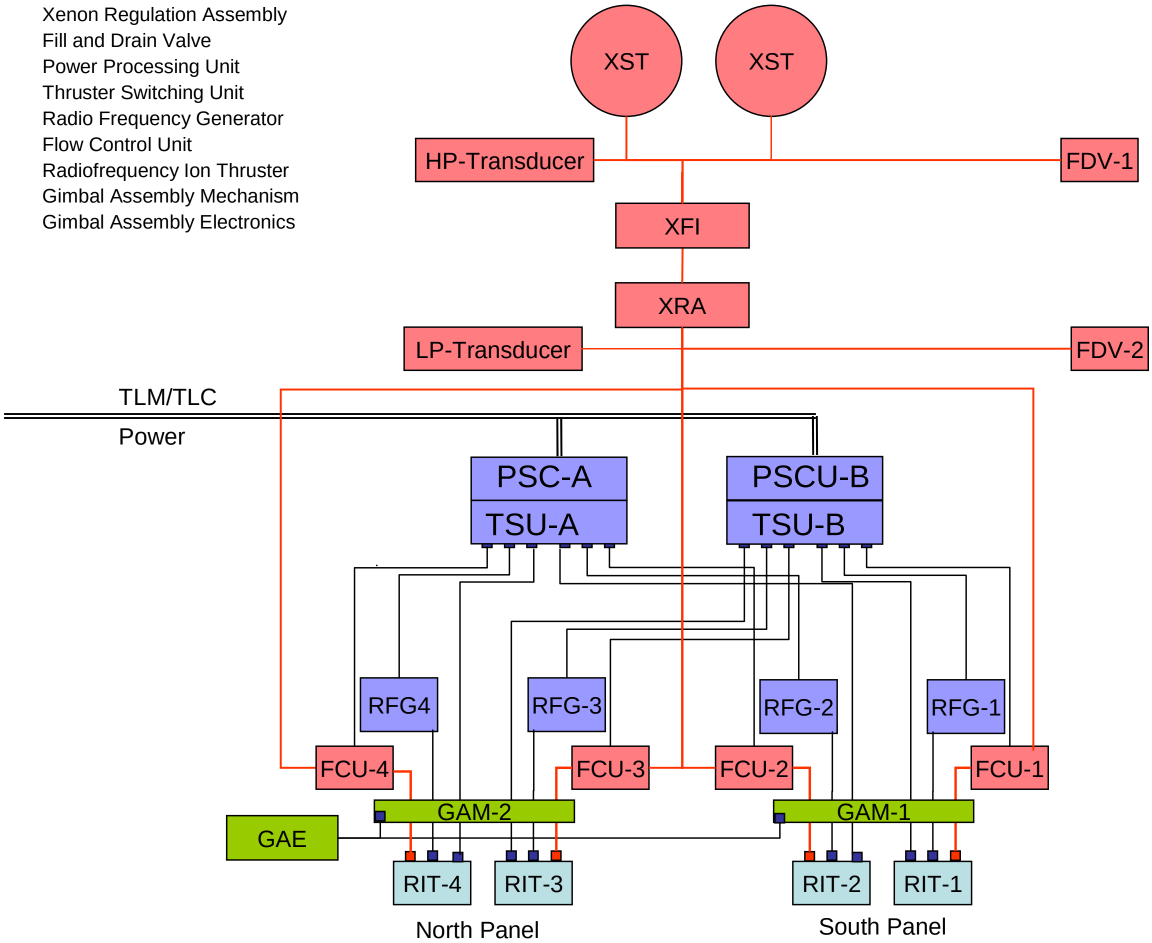

Figure 12 RIT based propulsion system for station keeping

Orbit Maintenance for Large Orbital Structures

During assembly and operation of the International Space Station ISS the upper atmosphere results in a reduction of the orbital height. This orbit decay is compensated by periodic re-boost manoeuvres using chemical propulsion. During the entire ISS Exploitation Phase, i.e. after the conclusion of the ISS integration the long time scenario predicts an average propellant demand of about 7,9 tons per year (using N2O4 + UDMH; specific impulse 300 s). This mass is equivalent to about 17 % of the average net transport capacity of about 46.4 tons/year to the ISS, which is a remarkable fraction.

To transport the propellant currently the European ATV and the Russian Progress capsules are foreseen. Alternative transports e.g. using the shuttle are currently not foreseen. As described above ion propulsion is capable to deliver specific impulses above 3000s. By this the propellant demand can be reduced to less than 1/10 of this number.

This enormous release of propellant mass on the other hand requires to install an additional power supply capability. To allow a continuous operation of a drag compensation ion propulsion system about 25 kW of electric power are required which is not avail able on the current system. Consequently a replacement of the current solar arrays by GaAs cells and the implementation of a solar dynamic power generator are needed.

The typical performance data of a solar dynamic ion propulsion system fort h ISS compensation the atmospheric drag is reflecting three boundary conditions:

- The ion propulsion is continuously compensation the drag compensation
- The solar dynamic power generator is used to compensate eclipse phases by using the energy stored as high temperature produced during solar radiation
- The solar energy is focussed to the absorber by means of a two axis pointing system

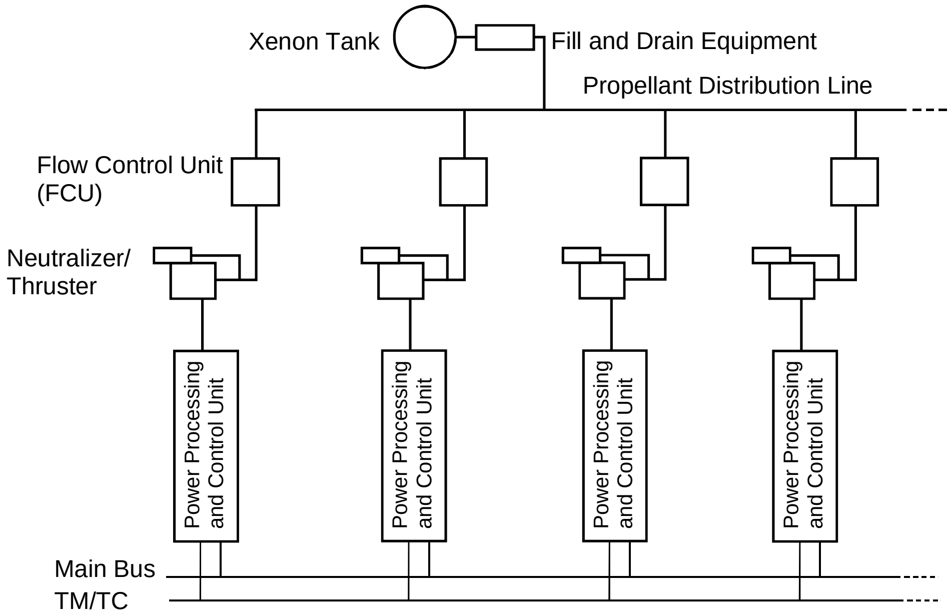

Figure 13 ISS Orbit raising System Block Diagram

A propulsion system requires:

• Thrust	0.5 N, continuously; to recover from phases where the thrusters have to be quiescent, 1 N should be available
• Specific impulse	5000s
• Xenon Mass Flow	$20*10^{-6}$ kg/s, continuously
• Beam power	15 kW average
• Total electric power	18 kW_e average
• Annual propellant demand	240 kg
• Life time	min. 5 years (44.000 h)

The proposed solution will allow to save a remarkable part of the transport cost. Assuming a transportation cost of 15.000 US $ / kg to the ISS the savings within 5 years will amount to 550 Mio US $. This saving potential off course has to be reduced by the cost required for development, procurement and transport of the hardware.

A typical system can be built modular to allow for a replacement of used up units by EVA activities:

- 10 RIT-22 thrusters delivering 150 mN each at ISP = 5000 s
  (7 units needed to produce 1 N)
- Total impulse per year: 4.7 10^7 Ns
- Thruster life lime > 2 to 3 years

As the thrusters need to be replaced in orbit a modular approach that allows an easy but reliable replacement by an EVA is required. Therefore it is proposed to replace a complete RITA assembly and to upgrade the module either on grounds or in the ISS laboratory.

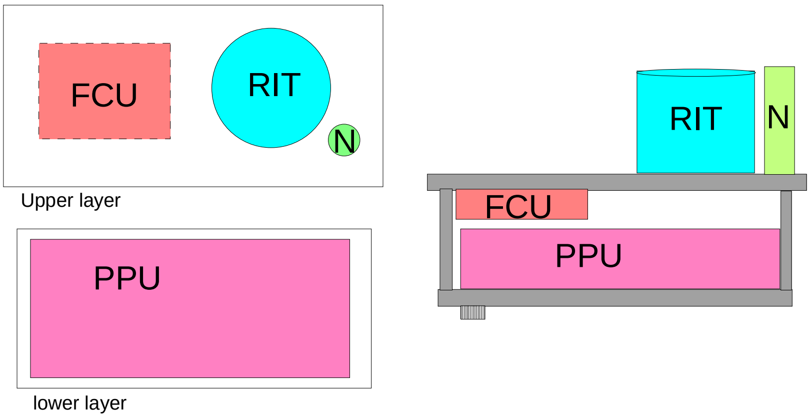

Figure 14 RITA module for ISS Application

The mass model blow shows that the hardware mass even in the first year will allow a net saving of 5,000 kg, allowing 1000 kg for the solar dynamic power generator.

I. Ion Propulsion System Mass (Example)

Component	Comp. Mass Kg	No. of Comp. -	Total Mass Kg	Dimensions mm
Thrust Module (150 mN)				
Thruster incl Neutralizer	7	1	7	300 dia. x 300
Flow Controller	1.4	1	1.4	100 x 80 x 80
Power Processing and Control Unit	18	1	18	810 x 360 x 140
Cabling/Tubing	1	1	1	--
Structure	2	1	2	
Subtotal per Module			**27.4**	
Propulsion System				
Total Module Mass	27.4	10	274	
Tank (1000 kg Xenon at 250 bar, 340K)	81	2	162	Total Volume: 560 dm^3
Feed System and System Tubing	10	1	10	--
System Power Harness	21	1	21	0.20 kg/m
HDS Harness	17	1	17	0.16 kg/m
Structure and Heat pipes	25	1	25	
Total			**509**	

V. Conclusion

Gridded ion propulsion onboard ARTEMIS has demonstrated its capability and reliability. Based on this the RIT-22 for large commercial satellites and deep space missions is under development and has demonstrated its performance and life capabilities during a set of tests, For the future the RITA technology offers the best perspective to deliver high and ultra high specific impulse for future deep space application or drag compensation of large orbital structures.

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