Development of the Radio Frequeny Ion Thruster RIT XT – A Status Report

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North south station keeping is no longer the only application for ion propulsion onboard satellites. A competitive thruster system should also cover the requirements of advanced orbital manoeuvers, especially orbit rising and de-orbiting. Astrium's new RIT XT thruster is designed to fulfill these demands. The potential free radio frequency ionization principle allows easily to adapt the ion propulsion system on high thrust demands of orbiting manouvers as well as high specific impulse operation during north south station keeping. Initially, a brief explanation of the thruster's function principle is given and the components of RIT XT are described. The test setup is explained and the most recent test results are presented.

I.INTRODUCTION

North South Station Keeping (NSSK) of heavy geo satellites is regarded as *the* commercial application for ion propulsion (IP). Only few years ago this was seen solely as future technology but nowadays IP has become "state of the art" for NSSK.

Also in the field of scientific missions electric propulsion is successful: Since "Deep Space One" is operated in space electric propulsion has become quite popular not only in the community of rocket engineers and scientists.

Due to significant improvements of solar cells and photo-voltaic electric power onboard spacecrafts increases continuously. Especially orbit and de-orbiting of satellites by ion engines will become possible in the near future. This will be the last, but decisive missing step to an "all electric satellite".

Commonly, ion propulsion is associated with Kaufman-type ion engines. Although this kind of thruster is indeed often considered, the radio-frequency ion engines, named "RIT" (*R*adio frequency *I*on *T*hruster) developed by Astrium GmbH and the 1st Institute of Physics at Giessen University are interesting alternatives. They combine the principal advantages of any gridded ion engine with the special features of ion generation by high frequency electromagnetic fields.

Up to now, RIT 10 is the solely *commercially* available *radio frequency* thruster. Over the years the nominal thrust of this engine ("10" characterizes the diameter of the thruster) could be enlarged from formerly 15mN (RIT 10 "ARTEMIS" configuration") up to a peak performance of 40mN (RIT 10 EVO), but it is obvious that this not sufficient to fulfill the requirements of the new generation of heavy geostationary communication satellites. Figure 1 illustrates that the daily operational time would exceed the upper reasonable value of 3hours of thrust-on time, if the satellite mass (Begin of Life, BOL) is significantly higher than 2000kg). Considering only NSSK a thrust of 100mN would be absolutely sufficient to operate even a Satellite of 6.000kg BOL. But in respect to offer a solution for more sophisticated orbit-control manaeuers Astrium Gmbh decided to develop an electric propulsion system of the 100-200mN class [1]. The system bases on a new thruster called RIT XT.

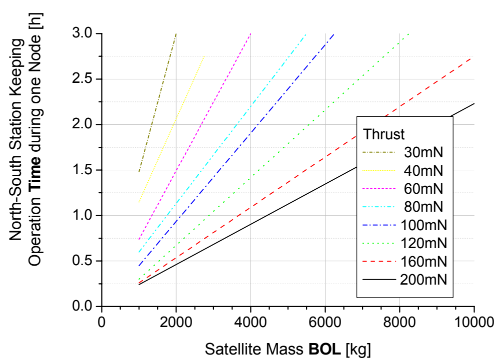
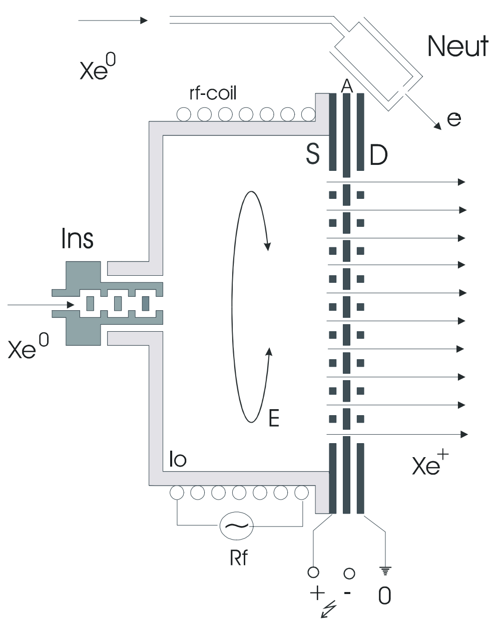


Fig 1 Operational Time for North South Staion Keepin in dependence of satellite mass for different thrust levels. It is assumed that the NSSK manoeover is performed only at one node once a day.



Io=Ionizer Chamber, RF=Radiofrequency Generator, Neut=Neutralizer, S=screen grid A=Accelerator Grid, D=Decelerator Grid (optional) , Ins=Gas inlet

Fig. 2 Function principle of RIT type radio-frequency ion thrusters.

III. RIT OPERATION PRINCIPLE

Radio Frequency Ion thrusters ("RF" – Thrusters") are operated without any hot cathode ("main cathode") inside the thruster's ionization unit [5,6 e.g]. 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 Maxwells 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 on 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 [9]. 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 has to be matched exactly to the resonance conditions given by the frequency of electromagnetic waves as well as on the 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 very *fast* changes of thrust level are necessary, because the desired thrust is reachable faster than milliseconds by simply changing the applied rf-power. Beam current and with that the thrust follows 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 were 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 backstreaming 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 backstreaming charge exchange ions generated in the downstream region of the ion beam hitting the acceleration grid. Also this third grid might have an influence of 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.

III. RIT XT

2.1. Heritage

RIT XT is Astriums first ion engine in the 100-200mN class. Nevertheless the development bases on a long term experience in ion thruster design and operation. Since the early sixties the NSSK engine RIT 10 has been continuously developed and improved. The first successful operation in space was performed onboard the European technology satellite EURECA.

Presently, Astrium GmbH offers an worldwide unique commercially available rf electric propulsion system called RITA (Radio Frequency Ion Thruster Assembly). RITA bases on the space qualified thruster system for ESAs new communication satellite ARTEMIS.

The corresponding lifetime test performed at ESA's test facilities at Nordwijk/NL of this engine is extraordinary successful. Up to now, the required 15.000h of operation have been nearly reached. When this paper releases, the lifetime test will be completed.

One of the most remarkable results of that test might be lifetime of thruster's graphite acceleator grids. The last inspection of the thruster performed at 13.000h of operation indicates a total grid lifetime in the range of 25.000-30.000h .

In the further description, that RIT 10 thruster will be named "RIT 10 ARTEMIS" to avoid confusion with the further developed RIT 10 EVO (EVOlution).

Meanwhile ARTEMIS was launched. Due to a failure at upper stage of the ARIANE launcher the satellite could not reach the geostationary orbit in the foreseen way by chemical propulsion. Thus the European Space Agency ESA worked out a strategy to orbit ARTEMIS by use of the NSSK electric propulsion system. Preliminary tests in space were already finished and begin of the orbiting manoeuver is scheduled for middle of November 2001.

2.2 Sub-scale Tests (RIT 10 EVO)

The evolution of RIT 10 is described because it could be proved that RIT engines of different size behave in the same manner (Development of RIT 10, RIT 15, RIT 35 at Giessen University). This opened the possibility to optimize the thruster's grid system on the smaller RIT 10 engine.

In a first step the grid system of RIT10 ARTEMIS was modified. The open area fraction was increased and the ion optics were modified. All the other parts of the thruster remained unaltered. This enabled to demonstrate the influence of the grid system on the performance data directly.

The result of the comparison between the RIT 10 ARTEMIS and the RIT 10 EVO is straight forward:

- *Thrust regulation bandwidth*
  The ARTEMIS thruster, qualified for 15 mN, was tested up to 18 mN. With the modified grid RIT 10 EVO could be operated between 1 to 41 mN.
- Increased *specific impulse* I_{sp} (thruster):

Thrust	RIT 10 ARTEMIS	RIT 10 EVO
15 mN	3400 s	3700 s
35 mN	n/a	3400 – 3700

- Reduced *acceleration grid current I_{acc}* The important lifetime limiting acceldrain current is reduced from 1,5% (RIT 10 ARTEMIS) to approx. 0,7% @ F≤30 mN (RIT 10 EVO).

  Please notice: Although a drain current of 1.5% seems rather high, the newest measurements of the RIT 10 ARTEMIS thruster's extraction hole diameters indicate a total lifetime significantly higher than 15.000h. It must be taken into account that the acelerator grids of RIT thrusters are comparably thick (now.1-1.2mm, typically 2.0mm in former times). Thus they collect an higher amount of charge exchange ions, but the resulting current hits the surface of the extraction holes on a larger area. Moreover the nearly one decade lower sputter yield of graphite compared with molybdenum and titanium leads to a smaller growth of extraction hole diameters. Consequently, the higher current does not result in a faster structural failure.

- Reduced *specific power consumption*:
  RIT 10 ARTEMIS reaches its nominal thrust of 15 mN only at a beam voltage of 1500V [2]. Thus the thrusters specific electric power consumption is physically given comparably high. In opposition to that the higher perveance *p* of the RIT 10 EVO grid set enables the same thrust level at a beam voltage of solely 900V. So the specific power consumption is remarkably reduced.

	$P_{thruster}/F$	$P_{mainbus}/F$
RIT 10 ARTEMIS	35 W/mN	37.5 W/mN
RIT 10 EVO	25-27 W/mN.	29-31 W/mN

Summarizing the comparison shows, that a modified grid system leads to an improvement of all important parameters: Maximum thrust, engine lifetime and thruster efficiency.

Same results concerning grid system and performance were found at Giessen Unversity during the development of RIT 15LP and RIT 15S, respectively. [4]

Moreover RIT 10 EVO shows an excellent behavior even at lowest thrust levels A special test program dedicated to applications like air drag compensation for low altitude satellites was performed in April and May 2000, under contract by ESA. The results of these tests are given in another paper [3].

In addition to the experimental work numerical simulations of the ion beam extraction and the entire thruster layout have been performed. The results of these calculations were in good agreement to the experimental data: Astrium GmbH could successfully validate their analytic tools.

Due to the excellent scalability of RI-Thrusters the testing of RIT 10 EVO is still ongoing. The results flow into the development of an advanced high thrust system directly.

2.3 Larger radio-frequency ion engines

Astrium gained their experiences with larger scaled ion thruster when building the ESA-XX engine. ESA-XX was a Bristish-German-Italian development of a 200mN primary propulsion thruster founded by the European Space Agency [4].

The ESA-XX rf-ion thruster itself bases on a laboratory prototype of a 35cm rf-thruster RIT 35, initially developed at Giessen University as a primary propulsion engine for interplanetary missions and an advanced extraction grid designed and manufactured in the UK.

During this project two important items were demonstrated: The successful operation of the radio frequency ionization at large scale thrusters and the influence of the thruster's grid system on the performance . Both aspects have been considered for the development of RIT XT.

2.4 RIT XT Description

RIT XT is designed to fulfil the demands of

- NSSK of heavy geosyncronous satellites
- Orbit raising of LEO-constellations
- Transfer from GTO to GEO
- Primary propulsion for interplanetary missions.

NSSK operation as well as primary propulsion of interplanetary probes are quite comparable applications of high specific impulse. A thruster layout similar to that of ESA-XX or Giessen Universities RIT 35 would have been sufficient for these demands.

In opposition, GTO and LEO missions require highest possible thrust at a limited power consumption. This means an increased ion beam current, respectively an increased ion beam density at lower beam voltages (typ. 900-1200V). Thus the efficiency of the propellant ionization is from major importance.

Any part of the thruster had to be analyzed in respect to the propellant utilization coefficient and the "ion production costs". As a result a new shape of the ionizer chamber was introduced.

Fig. 3 shows a cross section of RIT XT. The main difference to former RIT engines is obvious: That so far used cylindrical discharge vessel design is replaced by a conic one. The surrounding rf-coil is mounted directly on the surface of the discharge vessel.

It is anticipated at this point, that the shape has reduced the ion production costs and improved the propellant utilization. Besides that, the conic vessel has better mechanical properties, especially in respect to vibration loads and shock resistance during the rocket launch. Simultaneously the mass of the thruster is reduced.

Presently, the laboratory prototype design contains one special feature: A separate grid mounting ring. The complete grid package is removable from the discharge vessel in order to inspect the grids from the inner/plasma side. For that it is not necessary to disassemble the grid stack.

Thruster	RIT XT
Ionisation Principle	Radio Frequency Ionisation Frequency 0.7-1MHz
Beam Diameter	21 cm
Extraction Holes	8101
Screen Thickness	0.25mm
Screen Holes	1.9mm diameter
Accel Thickness	1.2mm
Dishtype	Outward

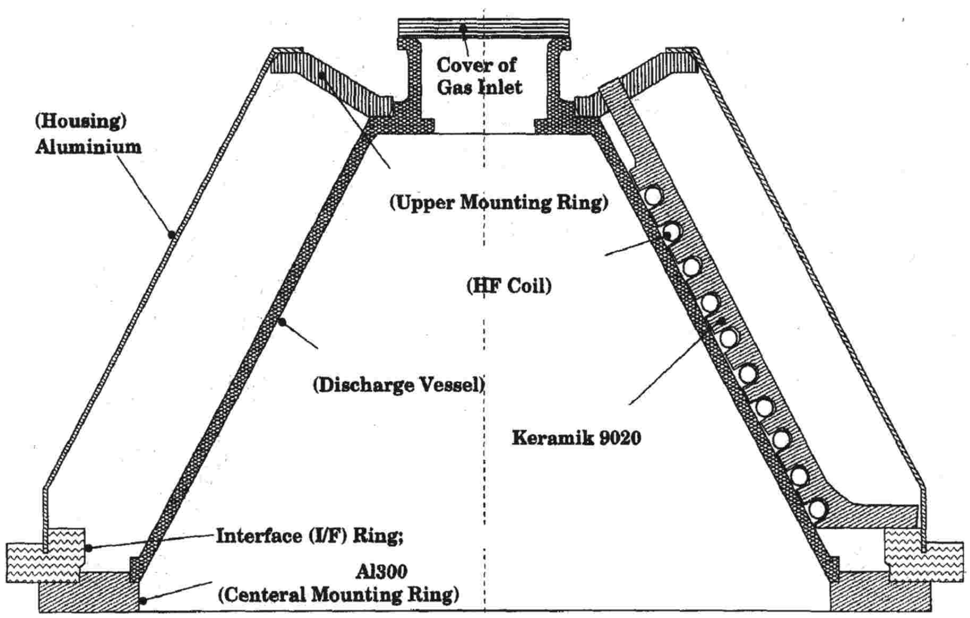


Fig 3: Cross section of RIT XT

Materials have been chosen in respect to the requirements of an rf-thruster:

- The thruster housing is made of aluminum
- For the discharge vessel alumina was selected
- The first grid sets of the prototypes were made of INVAR (Screen) and Graphite (Accel). Both materials were used in the RIT 10 and its derivatives since many years successfully. Meanwhile molybdenum has replaced INVAR as material for the screen.
- The rf-coil is made of copper.

III. Test Results

3.1 Test Facilities

There exists a long time companionship between Giessen University and Astrium GmbH in thruster testing and development and most of Astriums test campaigns were performed there. Also all RIT XT tests have been made at the "Jumbo Test Facility" of the 1st Institute of Physics.

The "Jumbo Test facility" consists of a main vacuum chamber (28 m^3 volume) and a thruster mounting chamber, called "thruster hatch" (1 m^3 volume). A gate valve separates the thruster hatch from the main chamber. So one has fast access to the thruster while the main chamber remains on high vacuum conditions.

For nearly thirty years of operation two large oil diffusion pumps (nominal pumping speed 100.000 l/s) generate the vacuum in the main chamber. Although these pumps work with unbeaten reliability the overall pumping speed of the system is nearly one magnitude lower than that of recently build up vacuum facilities. Therefore Giessen University decided to upgrade. The oil diffussion pumps will be replaced by a system of cryogenic pumps.

At the moment, the first step of the upgrade has been performed successfully. Four cryo-panels with a pumping speed estimated to 25,000l/sec each work in parallel with the oil diffusion pumps. Under these conditions the main chamber pressure remains below 1 x 10^{-3} Pa up to 75mN of thrust. This means that the given performance parameters, especially the acceleration drain current given in the following for higher thrust levels have to be regarded as preliminary. On the other side the newest results from XT-measurement are so interesting that we decided to publish them before the next step of the upgrade is finished. That will happen at the beginning of 2002.

3.2 Low Beam Voltage Operation

No other parameter determines the overall thruster characteristic as decisive as the beam voltage. In respect to a low/moderate power to thrust ratio (PTTR) the beamvoltage is selectable to 900V. The operational data are given in the next table.

As intended the power to thrust ratio is held bellow 24W/mN at a remarkable high specific impulse.

Thrust	50mN	75mN	80mN
Beam-voltage	910V	920V	920V
Accel-voltage	-150V	-160V	-170V
Beam-current	1000mA	1500mA	1600mA
Propellant utilization	80%	88%	91%*
Specific Impulse	2987s	3305s	3434s*
PTTR [W/mN]	23.98	23.29	23.33
Accel-current	8.8mA/ 0.88%	18.8mA/ 1.25%	21.4mA/ 1.34% *
RFG-input-power	245W	347W	371W *
Ion Production cost	232W/A+	219W/A+	220W/A+

* *refer to vacuum conditions*

\+ *For estimation of Ion Production Costs an electric efficiency of the radio-frequency generator of 95% was assumed.*

Even operation at higher mass utilization has been realized, but the gained data have to be confirmed under further improved vacuum conditions. From the present measurements a specific impulse of 3300s at begin of life (BOL) and better than 3000s at end of life (EOL) seems realistic.

3.3 Operation at nominal Beam Voltage

The operational data at low beam voltage indicate a high grid perveance (1.6A@1090V extraction voltage). This means a further increased beam current capability, if RIT XT is operated at 1200V or 1500V. Indeed the thruster reaches a thrust of more than 110mN@1200V and 125mN@1500V.

From the present state of work operation with 100mN and 120mN is recommended for these beam voltages. The operational data are summarized as follows:

Thrust	100mN	120mN
Beam-voltage	1200V	1500V
Accel-voltage	-180V	-180V
Beam-current	1775mA	1870mA
Propellantutilization	92.8%*	96%*
Specific Impulse	4054s*	4600s*
PTTR [W/mN]	25.7	27.17
Accel-current	25.7mA/ 1.45%*	34.0mA/ 1.85%*
RFG-input-power	376W	384W
Ion Prod-uction cost	198.4W/A+	190.8W/A+
Max. Thr. Temp.	263°C	279°C

* *Please refer to vacuum conditions*

\+ *For estimation of Ion Production Costs an electric efficiency of the radio-frequency generator of 95% was assumed.*

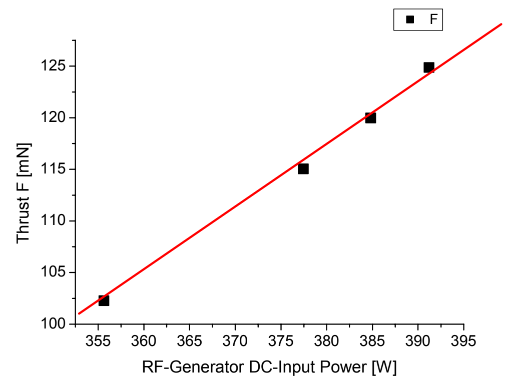


Fig. 4 Linearity between thrust and RF-power

The hottest point of an rf-thruster is usually near to the gas inlet. Here we found temperatures below 300°C. So the thruster's thermal load is moderate and easy to handle.

Besides the pure performance data it is remarkable that RIT XT shows the same linearity between supplied rf-power and beam current, respectively thrust as its smaller relatives RIT 10 EVO and RIT 15°LP (S) (Fig.4).

3.4 Outlook

The original design coals for RIT XT have been demonstrated successfully. Now, the further work will be focused on a more detailed study of the so far reached operational points. Especially beam diagnostics are still missing due to the ongoing upgrade of Giessen University's vacuum facilities.

The high performance of the new generation of rf-thrusters developed in Germany forced a new concept for beam diagnostic measurements because high ion current densities inside the thruster's beam lead to significant thermal stresses and sputter erosion of any measurement device placed inside the beam area. Besides the damage of the measurement equipment itself back-sputtering of particles in direction to the thuster is a serious problem: Metallic atoms might form conductive coatings inside the thruster and/or in its extraction grid system.

The new measuring system under construction will be fully movable in all three axis. If no measurements were made it will be driven outside the beam. So back-sputtering towards the ion thruster occurs only for very short time. The resulting effects should be negligible

A further advantage of the new basic measurement system is to carry different types of probes. So a flexible response to all demands of measurement will be possible.

Another point our work is presently focused on is high specific impulse operation. As far as a new high voltage power supply is delivered and installed the thruster will be operated with 1750V/2000V beam voltage.

Considering the present data and operational behavior of RIT XT a specific impulse of 4500s-5000s is expected

CONCLUSION

Astrium GmbH has reinforced its electric propulsion activities. In 2001 the new advanced RIT XT thruster reached the foreseen operational data. Successful operation with beam voltages of 900V, 1200V and 1500V was demonstrated. The RIT XT thruster with a beam diameter of merely 21cm is capable to deliver a thrust of more than 125mN. The future work is focused on two aspects. The so far done measurements have to be completed by beam diagnostic results and operation at further increased beamvoltage is planed. For a beam voltage of 2000V a thrust of 150mN is expected.

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