DEVELOPMENT AND PERFORMANCE OF THE ADVANCED RADIO FREQUENCY ION THRUSTER RIT-XT

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Abstract

The trend of a significant increase in mass and size of geo-stationary satellites from generation to generation of spacecraft is still ongoing. In parallel, the demands on the satellite's propulsion systems for all kinds of orbital maneuvers are growing. Beside higher thrust level the propulsion system's efficiency becomes to a key factor for economical success of the future satellite platforms. The efficiency is expressed in the propulsion systems specific impulse and electric efficiency. For some maneuvers the specific power to thrust ratio replaces the electric efficiency as decisive factor.

Ion propulsion (IP) enables for a more than ten times higher specific impulse than conventional chemical systems. For a long time IP was regarded only as a solution for North South Station Keeping (NSSK) of geo satellites and auxiliary propulsion of interplanetary probes. But under commercial aspects the propulsion system should also cover the requirements of extended orbital maneuvers. Especially, spiral-up and de-orbiting of satellites is from growing interest. Astrium's RIT-XTthruster is designed in respect to the bandwidth of these demands. In addition to the general advantages of IP Astrium takes benefit of the employment of potential free radio frequency (rf) ionization principle. The rf ionization leads to an unbeaten simplicity in the thruster design enables for highest system reliability.

After a short introduction into the advantages of IP 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. These results include operation with a specific impulse between 3000s-5200s and a thrust level up to 200mN

I. Introduction

Performing North South Station Keeping (NSSK) of heavy geostationary satellites by ion propulsion (IP) realizes significant economical benefits. IP uses the limited propellant onboard of the spacecraft roughly ten times more efficient than chemical propulsion, five times better than arcjet technology and at least more than two times better than stationary plasma thrusters. Thus the higher mass efficiency of IP allows for a reduced satellite launch mass, a higher pay-load or a longer satellite lifetime. Alternatively the best combination of these three possibilities can be realized for maximum benefit under given economical constrains.

Only a few years ago IP was still regarded as a future technology. In the meantime, IP has become "state of the art" for NSSK.

Since the American space agency NASA operated "Deep Space One" very successfully in space the idea of IP as propulsion for deep space missions is accepted. Moreover that mission mad IP very popular, not only in the community of rocket engineers and scientists.

Consequently, after the “Deep Space One” technology demonstration mission, IP establishes now for advanced scientific missions. One of the most ambitious projects among them is European Space Agency’s (ESA) mission to mercury, BepiColombo. Besides the high specific impulse and thrust demands, especially the thermal conditions make this mission so challenging. The design of adequate ion thrusters requires a lot of experience and knowledge in ion thruster development.

Both types of applications, NSSK as well as interplanetary space flight are quite similar in respect to the requirements. The key parameter is in both cases the thruster’s specific impulse.

A different situation occurs when orbiting and de-orbiting satellites: The profile of requirements shifts from high specific impulse operation towards a moderate power to thrust ratio combined with a medium specific impulse. Even if the PTTR is reduced, the total power required to perform such maneuvers was too high up to now. Presently, the situation changes: Due to significant improvements of solar cells and photo-voltaics, electric power onboard spacecraft has overcome the threshold for these extended maneuvers. The last, but decisive missing step to an “all electric satellite” seems near.

In contrast to other electric propulsion technologies, IP provides the possibility to vary specific impulse and PTTR in a considerable range. Astrium’s new Radio Frequency Ion Thruster Assembly “RITA” uses this advantage and is designed to fulfill the demands of high specific impulse applications: NSSK as well as interplanetary missions on the one hand side and advanced orbital maneuvering on the other side. The main unit of the propulsion assembly is the radio-frequency ion thruster RIT.

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 benefit from numerous advantages. They combine the principal advantages of any gridded ion engine with the special features of ion generation by high frequency electromagnetic fields.

II. RIT Operation Principle

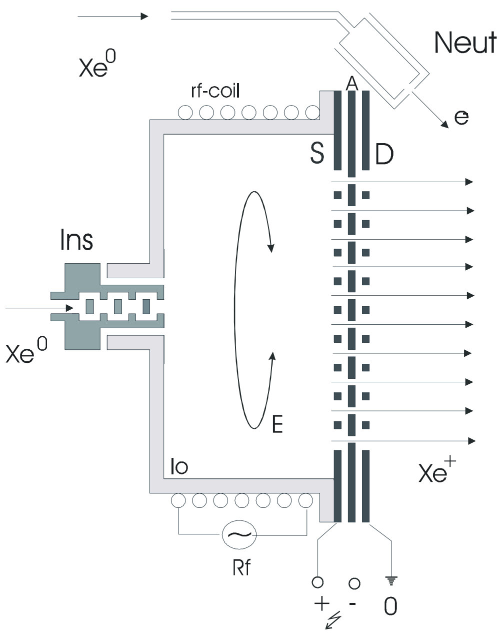
Thrust generation in gridded ion thrusters is a process consisting of two steps. The thrust itself is generated by acceleration of electrically charged propellant particles in static electric fields. Therefore it is necessary to ionize the propellant in the step before.

Radio Frequency Ion thrusters (“RF” – Thrusters”) are operated without any hot cathode (“main cathode”) inside the thruster’s ionization unit [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 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 [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 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. 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.



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

Fig. 1 Function principle of RIT type radio-frequency ion thrusters.

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 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 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.

III. RIT_ XT

3.1. Heritage

The RIT-XT is Astrium’s 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. It was the first flight of an European ion propulsion system in space. The 10cm ion engine has been continuously further developed. A new milestone ion propulsion is reached with the development of RIT 10 for the ESA’s technology satellite ARTEMIS .

RIT 10 and RITA 10 for ARTEMIS

Astrium completes its ion thrusters to a system called “radio-frequency ion thruster assembly” (RITA) with all necessary components for thruster operation as flow control, power supply, radio-frequency generator and control electronics. This system is operated successfully in ground test and in space.

Lifetime test

As part of the ARTEMIS qualification program a full lifetime test of the RIT 10 engines was performed at ESA’s test facilities at Nordwijk/NL. The required 15.000h of operation together with all other envisaged parameters were reached in autumn of 2001 without problems. It is underlined that the entire system RITA 10 including all components and not only the thruster itself was tested over the full required time.

Although the test has been completed successfully at this point it was decided to continue in respect to the not foreseen orbit raising maneuver of the ARTEMIS satellite. The test set-up allows to check out the behavior of miscellaneous tasks before realizing in orbit. One of the most remarkable results of that test is the lifetime of the thruster’s graphite accelerator grids. The inspection of the thruster performed after 15.000h of operation indicated a total grid lifetime in the range of 25.000h. Testing was abandoned in December 2002 at still fully operational thruster after more than 20.000h of operation.

In flight experience and orbit-raising

In August 2001 ARTEMIS has been launched. Due to a malfunction of the upper stage of the launcher the satellite could not reach the geostationary orbit in the foreseen way by chemical propulsion. Thus Alenia and Astrium together with the ESA worked out a strategy to raise the ARTEMIS orbit by use of the small NSSK electric propulsion system. After the mandatory initial tests in space were successfully completed the orbit raising begun. In January 2003, when this publication was written the Satellite has nearly reached its final orbit. The RITA 10 ion propulsion system was operated for more than 5500h continuously in space Although SPTs are often regarded as an superior technology for orbit raising and orbit topic maneuvers it is a small ion engine which performs the first orbit raising of a heavy geo-satellite!

3.2 Sub-Scale Tests (RIT 10 EVO)

In the further description, the successful thruster of the ARTEMIS mission will be named "RIT 10 ARTEMIS" to avoid confusion with the now discussed further developed RIT 10 EVO (EVOlution).

The evolution of RIT 10 is described here because it provided the basis for the RIT-XT development. It was successfully proved, that RIT engines of different size behave in the same manner (Development of RIT 10, RIT 15, RIT 35 at Giessen University). This opens the possibility to optimize the thruster on smaller sized engines to save time and costs.

In a first step the grid system of RIT 10 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 the RIT 10 EVO is operable 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 accelerator drain current is reduced from 1,5% (RIT 10 ARTEMIS) to approx. 0,7% @ F≤30 mN (RIT 10 EVO).

  Note: 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 higher than 25.000h. It must be taken into account that the accelerator 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 order of magnitude 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*:
  The 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 contrast to that, the higher perveance *p* of the RIT 10 EVO grid set enables the same thrust level at a beam voltage of merely 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.

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

Moreover, the 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 of ESA. The results of these tests are given in [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 the RIT 10 EVO is still ongoing. The development of an advanced high thrust system benefits directly from these results.

3.3 Larger Radio-Frequency Ion engines

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

Astrium was responsible for the thruster layout and the manufacturing of the discharge chamber and all components excluding the grid system. The advanced extraction grid was designed and manufactured in the UK by AES technologies. The thruster’s neutralizer was manufactured in Italy by PROEL.

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.

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.

3.4 RIT-XT Description

About 3 years ago, astrium decided to develop a high thrust ion engine for commercial and scientific applications. The Development Model of the corresponding thruster is the RIT-XT, which has been in development and testing for approximately 2 years now. Meanwhile, the thruster development process has been continued according Astrium’s development schedule and the Engineering Model is well under progress. The following thruster description refers to the RIT-XT.

RIT-XT is designed to fulfil the demands of

- NSSK of heavy geo-synchronous satellites
- Primary propulsion for interplanetary missions.
- Orbit raising of or orbit topping of geo-synchronous satellites
- Orbit raising of LEO-constellations

As mentioned before, NSSK operation as well as primary propulsion of interplanetary probes are quite comparable applications concerning the high specific impulse. A thruster layout similar to that of ESA-XX or Giessen University’s RIT 35 would have been sufficient for these demands.

In contrast, missions involving partial orbit raising ("orbit topping") 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 of 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. 2 shows a cross section of RIT-XT prototype. The main difference to former RIT engines is obvious: The so far used cylindrical discharge vessel design is replaced by a conical one. The surrounding rf-coil is mounted directly on the surface of the discharge vessel.

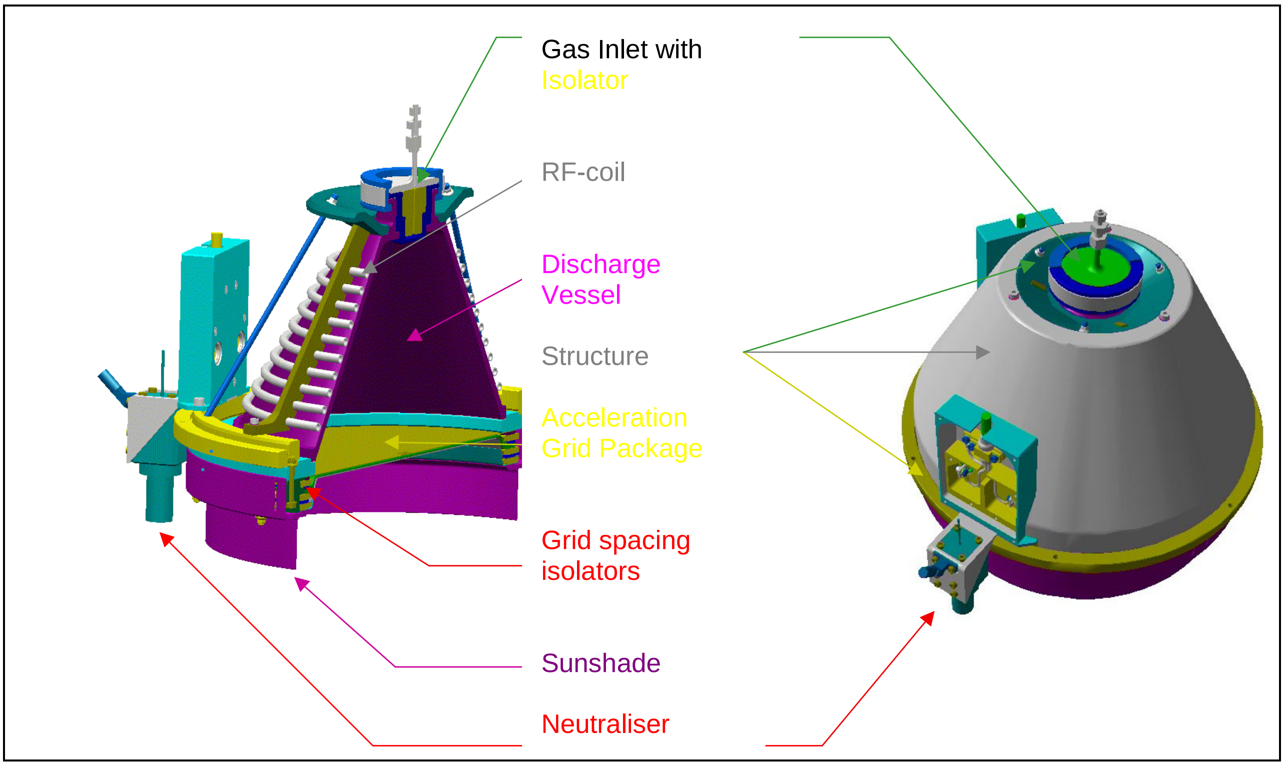
It is anticipated at this point, that the shape has reduced the ion production costs and improved the propellant utilization. Besides that, the conic vessel has better mechanical properties, especially in respect to vibration loads and shock resistance during the rocket launch. At the same time the mass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

The 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. This design feature allows for rapid inspection cycles and quick exchange of grid designs in the grid optimization loop in order to minimize test interruptions.

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

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 have been successfully used in the RIT 10 and its derivatives since many years. Meanwhile molybdenum has replaced INVAR as material for the screen.
- The rf-coil is made of copper.



IV. Thruster Testing

4.1 Test Facilities

A long time companionship between Giessen University and Astrium GmbH exist in testing and development of ion thrusters and most of Astrium's test campaigns were performed at Giessen. 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. This allows for fast access to the thruster while the main chamber remains on high vacuum conditions.

The "Jumbo Test facility" has been known for its huge oil diffusion pumps. For nearly thirty years of operation two oil diffusion pumps (nominal pumping speed 50.000 l/s each) have generated 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 built-up vacuum facilities. Therefore Giessen University decided to perform an upgrade of the facility. Meanwhile the oil diffusion de-mounted. The vacuum chamber is operated employing the new high performance cryo-system.

4.2 Low Beam Voltage Operation

Any other parameter determines the overall thruster characteristic as decisive as the beam voltage. In respect to achieve a low/moderate power to thrust ratio (PTTR) the beamvoltage can be reduced to 900V.

In ref. [10] the first preliminary data of this operational regime were published. Since that time, the performance evaluation has been continued. In principle, the preliminary data could be confirmed. Only a small leakage in the propellant feedline was identified which caused a diminished mass efficiency in the first measurement period. In addition, the performance was still limited due to the maximum available output power of the radio-frequency-generator (RFG). The operational limits of the RGF were set to reduced values for safety of the device. Since thruster and RFG behaved as predicted in the first test campaign, the restrictions were suppressed and the RFG was operated up to its full operational limits. At a beam voltage of 920V a maximum thrust of 125mN was demonstrated using the described laboratory prototype in a second test campaign [11]. In schedule the next test campaigns were started. All predicted performance values were successfully demonstrated.

4.3 Operation at 2000V Beam Voltage

In respect to the requirements for NSSK and interplanetary missions the engine's specific impulse *Isp* is the key parameter. To ensure a system *Isp* above 4500s the acceleration voltage is set to 2000V.

It was pointed out in the description of the RIT function principle, that the thrusters have a broad operational range in respect to the mass flow (mass efficiency respectively). This behavior can be found in the following table. At a thrust levels of 100mN the mass efficiency was varied between 70% up to 95%. At higher thrust level the bandwidth was limited by the operational range of the RFG on the one hand and the increasing accelerator drain current at low mass efficiencies on the other hand.

In principle, no restrictions for higher beam voltages apply, the limit in the performed demonstration was the critical electrical field strength between the screen- and the accelerator-grid. The RIT-XT grid is of course optimized for the operational beam-voltages between 900V-2000V.

4.4 Thrust Linearity and Stability

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.3).

The linearity between rf-power and ion current together with the operational bandwidth in respect to the propellant mass flow on anx thrust level are the basis for an excellent thrust control (Fig. 4).

Fig. 5 demonstrates how the system responds to a variation of the propellant flow rate:

After the “thrust-on” order the system reaches the commanded thrust of 100mN immediately. Due to the warm-up of the discharge vessel the rf-power is increased to hold the beam-current (thrust) constant. When the mass flow is increased the system responds with a decreased rf-power. This has of course an effect on the thruster’s specific impulse, but the thrust remains constant during the whole cycle.

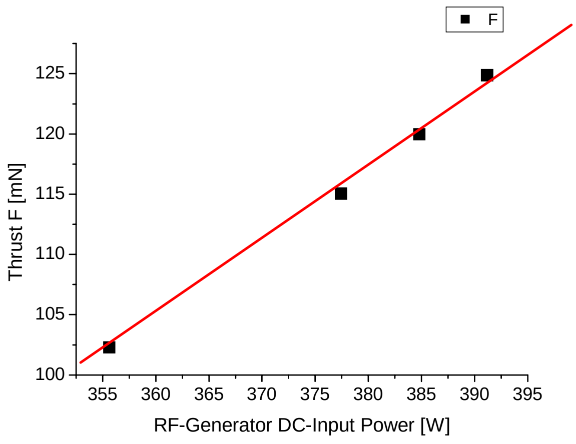


Fig. 3 Linearity between thrust and RF-power

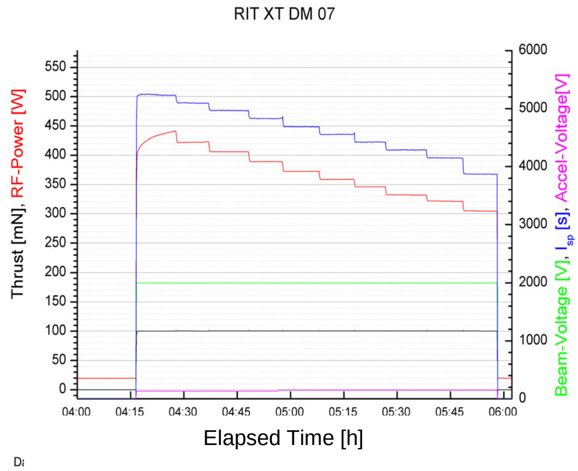


Fig. 5 RIT-XT Thrust control

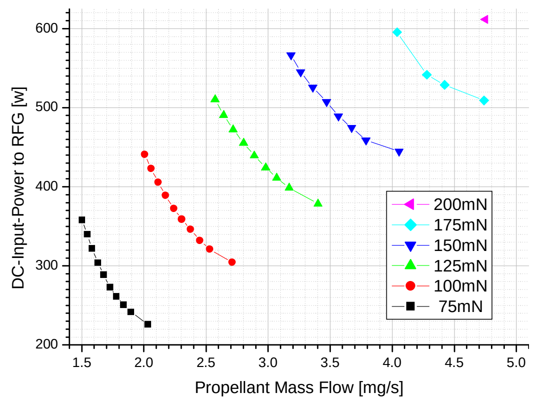


Fig. 4 (Left) Operational bandwidth: The Thruster is fully operable at any thrust level over a wide range of propellant mass flow. (Data of laboratory engine to demonstrate engine behavior, not representing the *performance* of flight type)

V. CONCLUSION & OUTLOOK

In 2001/2002, the RIT-XT thruster reached the designed operational data. Successful operation with beam voltages of 900V, 1200V and 1500V was demonstrated. In the meanwhile the performance evaluation was continued. On schedule, the thruster has demonstrated operation in an high-specific impulse mode (Is>5000s). The peak performance is a specific impulse higher than 5500s and a thrust of more than 200mN. The RIT-XT shows an excellent thrust control behavior.

The future potentiality of the rf-technology in respect to ultra-high specific impulse operation was demonstrated successfully.

Astrium’s development of a radio-frequency ion propulsion system is on schedule.

All necessary activities to offer to the customer a competitive, high-performance Ion Propulsion System are under progress.
A Team of well-experienced European Partners is set up to meet the challenging development schedule and market requirements.

For commercial applications, the development is focused on large telecommunication satellite platforms such as the Alphabus project.
Adaptability to the specific requirements of scientific missions through minor will be taken into account in the hardware and requirement definition.
The commercial propulsion system consisting of the thruster unit, power supply and control unit, rf-generator and xenon flow control unit is scheduled to start its qualifying system life test (t>15.000h) in early 2005.

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