Radio-Frequency Micro Thrusters and Their Applications

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Annotation

Since a couple of years, scientific European Space Agency missions like «Post Goce», «NGGM», and «LISA» are being prepared which need a very precise micro-thrusting in the range of 50 to 2500 μN. Thus, in 2004, Giessen University started a scaling-down program of the standard RIT-10 engine. Three mini-thrusters have been built and tested, whereby the 2.5 cm device, called μN RIT-2.5, reached the status of an advanced breadboard model. Following extensive optimization tests at Giessen, the thruster was operated at the Nanobalance Facility of Thales Alenia, Torino/Italy under ESA/ESTEC contract. Thrust range and linearity, thrust resolution, thrust noise, and response time have been measured showing that the μN RIT-type would be a good candidate for micro thrusting on the above mentioned satellites and spacecrafts.

Keywords

spacecraft; radio-frequency ion thruster (RIT); electric propulsion (EP)

Introduction

The principle of a radio-frequency ion thruster (RIT) has already been invented at the 1st Physical Institute of Giessen University in 1962. It is based on an electrodeless gas discharge to ionize the propellant (nowadays xenon). For that, the ionizer vessel, made e.g. from aluminum oxide, is surrounded by the induction coil of an rf-generator. An electrical eddy field is induced that accelerates the electrons of the discharge plasma to enable them for further ionizing collisions.

Two or three multiply perforated electrodes biased on high voltage (e.g. +1500 V, -500V, 0) extract the plasma ions, accelerate them, and form a thrust generating ion beam. The thrust depends on the plasma density, the positive high voltage and on the number of extraction holes.

At the beginning, a 10 cm ionizer diameter thruster RIT-10 has been developed, optimized, diagnosed and tested at the institute. Giessen's industrial partner, (now named) EADS Astrium ST, qualified it for space and used it onboard two ESA satellites in 1992 and 2002/2003 (Figure 1, left).

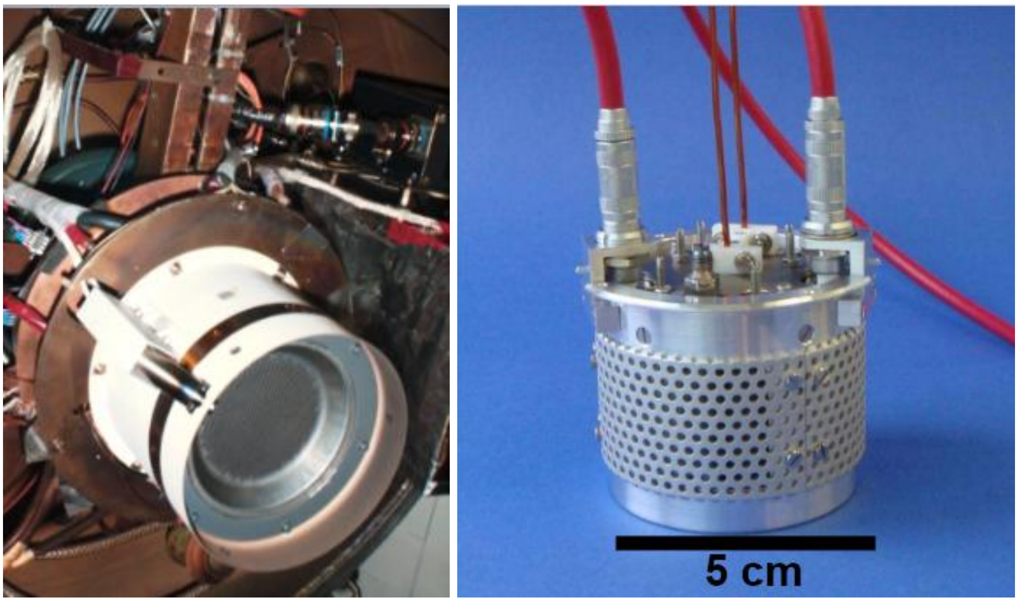

Figure 1 - RIT-10 thruster of EADS Astrium ST on ESA's satellite «Artemis» (left) and 2.5 cm breadboard mini-thruster μN RIT-2.5 of Giessen University (right)

Already around 1970, programmes for scaling-up as well as for scaling-down of the «father» of today's RIT family was started at Giessen. A RIT-4 was built and tested producing 1 to 2 mN. As no application came into view at that time, this special development line has been terminated.

The situation changed at the beginning of the 21 century when some ESA and US projects needed ultrafine electric propulsion (EP) thrust levels and when the originally envisaged microthrusters that operate without gas discharges could not overcome inherent problems.

So, the Giessen scaling-down programme has been revived in 2004. Based on the experiences of the past decades and on scaling laws within the RIT family, two laboratory engines with 4 cm and 2 cm of ionizer diameter have been designed, built and tested at the 1st Institute of Physics. The first results could be reported already in October 2004 at the International Astronautical Congress in Vancouver.

While EADS Astrium ST is now developing a 4 cm engineering model for ESA/ESTEC, Giessen University is testing intensively a 2.5 cm advanced breadboard prototype also under ESTEC contract (Figure 1, right).

Micro-thruster Applications

During the last decade, some scientific missions have been considered planned or are even already in preparations that need EP-microthrusters. We describe two examples:

- Following the Earth observation satellite «GOCE» which mapped the gravity field and the ocean circulation, a «POST GOCE», a «GRACE» (Gravity Recovery and Climate Experiment) as well as «NGGM» (Next Generation Gravity Field Mission) are considered. Figure 2 shows the design of a NGGM-spacecraft. In orbit, two identical satellites will fly in formation to improve the precise measurement of «g». The task of EP will be attitude and orbit corrections (AOC) and satellite-satellite tracking, as well as atmospheric drag compensation.

- Figure 3 shows pictures and drawings of «LISA» (Laser Interferometer Space Antenna) which should detect gravitation waves (coming e.g. from a supernova explosion or a black hole) and test in this way also Einstein's general relativity theory. LISA consists of three spacecrafts positioned in space at the corners of an equilateral triangle and connected by lasers. The task of EP would be a very exact position and attitude control as well as the compensation of disturbing effects by solar light and solar wind pressure.

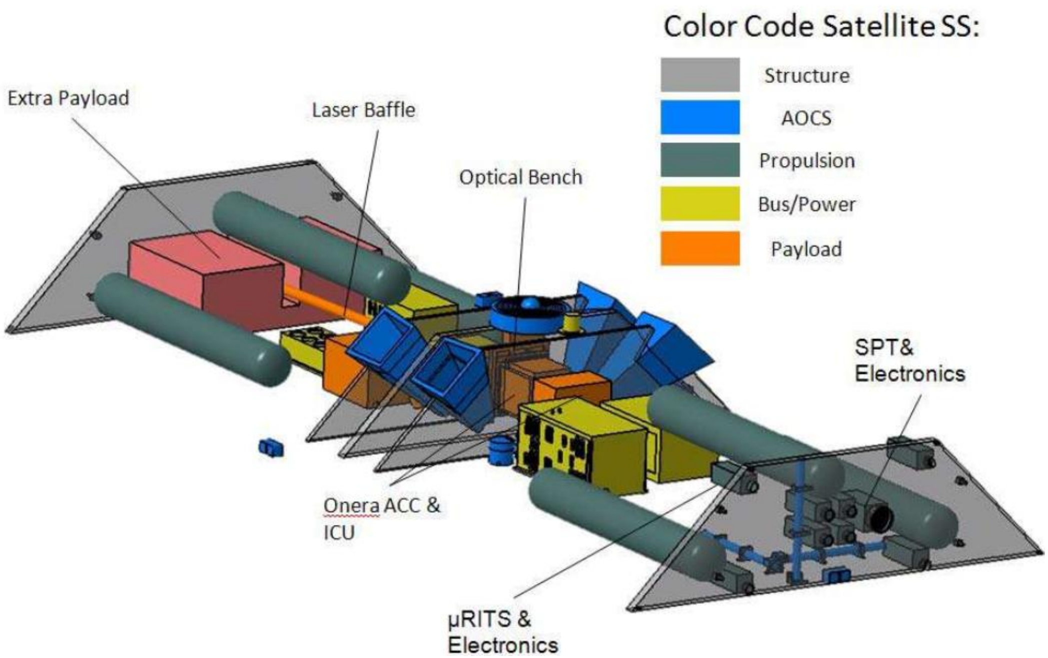

Figure 2 – Design of the «NGGM» satellite with µRITs on board

Actually, a single spacecraft «LISA Pathfinder» is being prepared for testing in space (see photo on Figure 3 up, left).

We mention a postponed project «DARWIN» that should be composed by a fleet of e.g. 5 spacecrafts to build up a very large telescope looking for Earth-like extrasolar planets.

For all these applications, the specifications for the EP-thrusters are rather hard:

- Very high thrust dynamics 50…2500 µN, whereby the coarse thrusting range (≥1 mN) is needed for satellite drag compensation, for approach of spacecrafts to their operation point in space and for reorientation of telescopes to other targets, whereas the fine thrusting range (< 1 mN) is needed for a highly precise AOC and for compensation of photon and particle radiation of the Sun,
- Thrust resolution and regulation < 1 µN,
- Very low thrust noise < 0.1 $\mu N/\sqrt{Hz}$,

- Specific impulse 1000 … 5000 s,
- Thrust rise time < 10 ms, thruster lifetime > 50,000 hrs,
- Low power consumption and low thruster mass.

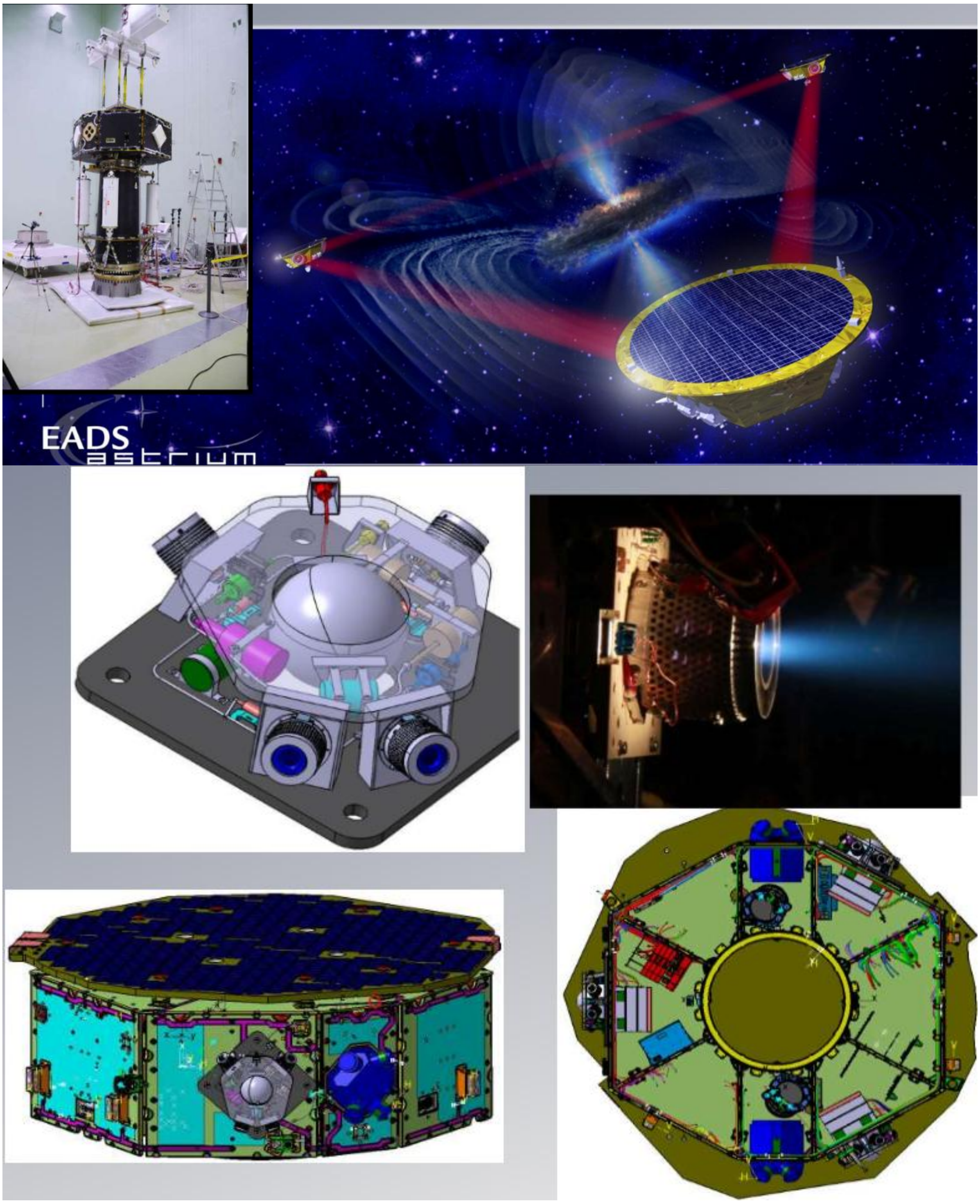

Figure 3 – Artist's drawing of «LISA» with 3 spacecrafts, a photo of «LISA-Pathfinder» (left), three technical drawings of it and a photo of a µN RIT-engine during operation

Problems of scaling-down and performance of µN RIT-2.5

Due to the electrodeless ionizer and the absence of magnets, it is much easier to scale down a RIT-engine than a Kaufman-type ion thruster or a SPT-motor. Thus, the RF-type is favorable among all engines working with gas discharge.

However, physical laws and the mode of working make the performance of micro engines worse with respect to the larger rf-engines, and require very careful optimization.

Firstly, the ratio of the ionizer surface (where the main plasma losses appear by ion-electron recombinations) versus the ionizer volume (where the plasma is generated) increases with the ionizer size reduction which leads to higher ion production costs. This pure geometrical effect is even enhanced by the empirically found optimum discharge vessel length that is for RIT-2.5 73 % of the diameter (for RIT-10 only 45.7 %).

Secondly, the energy accumulation process of the discharge electrons in the induced electrical eddy field (sketched in the introduction) requires elastic collisions with neutrals. So, shrinking ionizer dimensions make an increasing of the gas pressure necessary that results in decreasing propellant efficiencies and specific impulses.

Thus, the Giessen µN RIT-25 engine has been carefully designed and optimized. The ionizer got a dome-like shape, and the xenon propellant injector channels were drilled through the emitter grid near the ionizer wall.

To minimize the RF-power consumption, i.e. to optimize discharge vessel and rf-coil geometry, the magnetic field of the coil current has been computed (see e.g. Figure 4).

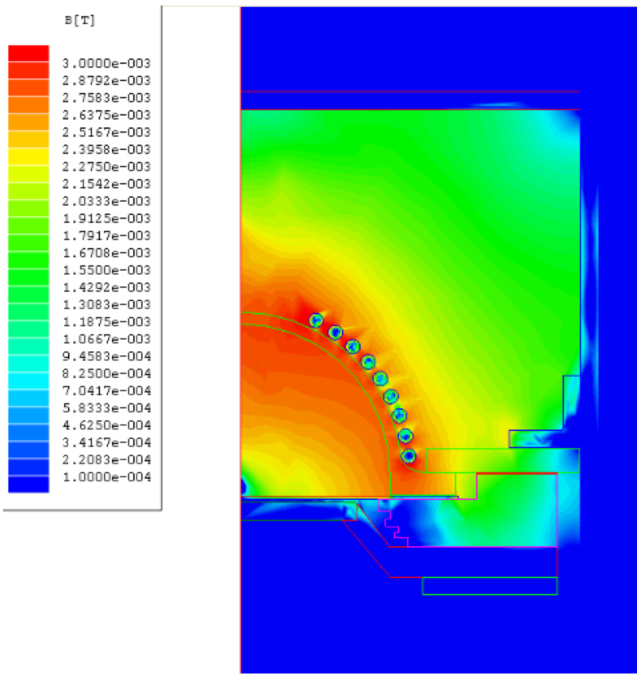

Figure 4 – Magnetic field (in Tesla) of the induction coil of a small RF-ion thruster used to minimize its RF-power consumption

The two-grid extraction system had 37 borings with the standard geometry.

The complete thruster weights only 210 grams. The thrust dynamics was between 50 and 500 μN. However, the specific impulse of 4000 s yielded at maximum thrusting could no be kept when throttling down because a too strong diluting of the discharge plasma at unchanged extraction voltage, i.e. at constant I_{sp}, would cause a direct impingement of the accelerator electrode due to an over-focusing of the primary beamlets.

Thrust Measurements

By ESA/ESTEC contract, a Giessen μN RIT-2.5 mini engine has been tested on the micro-thrust balance of Thales Alenia at Torino, Italy. (An identical but inactive second thruster was also installed for mass balance). Figure 5 gives the thrust control scheme power supply and control unit (PSCU) of the operated engine. Figure 6 shows photos of the vacuum tank and the thruster mounted on the «Nanobalance Facility». The results of the test campaign were:

- Thrust range and linearity:
  Figure 7 shows the post processed data of the first test run where the thrust was increased and later decreased in 50 μN steps from 60 μN to 650 μN. One sees also that the measured thrust (by nano-balance (NB)) coincides with the computed data (micro-thruster control unit (MTCU)).
- Thrust resolution:
  Figure 8 shows the resolution at 150 μN (left) and 550 μN (right), respectively, during test runs of about one minute. The control electronics allow to command the mini-RIT with a resolution of about 0.1 μN. The minimum detectable thrust steps during the tests were 0.3 μN and 0.5 μN, respectively that are compliant with the NGGM requirements (see above). Excessive background noise of the nano-balance prevented the detection of smaller steps and the measurement of the thrust resolution above 550 μN. This upper limit is the result of heating the balance by the microthruster.
- Thrust noise:
  Figure 9 shows the thrust noise density, given as usual in $\mu N/\sqrt{Hz}$, versus the frequency f. We have to distinguish between the residual gas flow as polluter (at minimum and maximum thrust level) and the ion current itself. The graph demonstrates that the thrust noise of μN RIT-2.5 is well below the LISA specification.
- Response time:
  Figure 10 shows a measured thrust rise time of 85 ms when the engine is started from zero running up to 50 μN. The same value was found for the thrust fall time (from 250 μN to zero). If

the nano-balance measured in wide band, rise and fall times became much lower. But in general, the named times are in accordance with any gas discharge ion source.

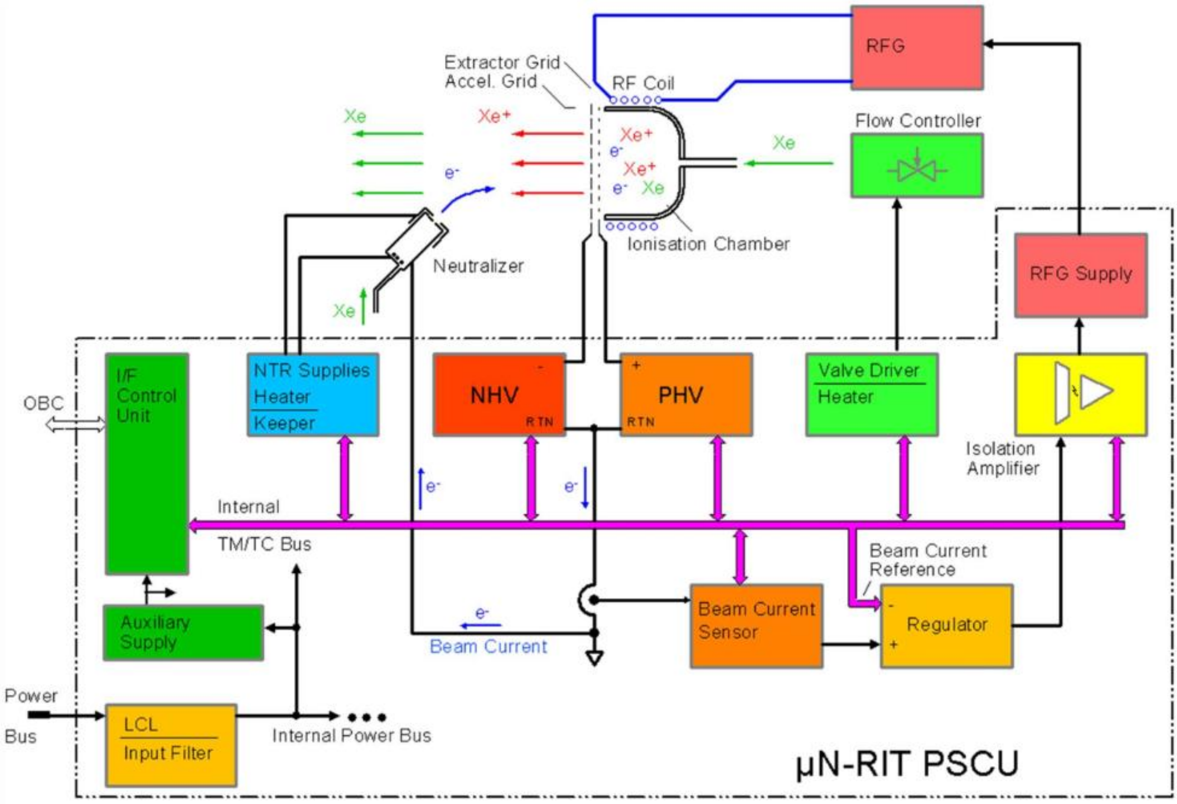

Figure 5 – PSCU of a micro-Newton RIT-engine

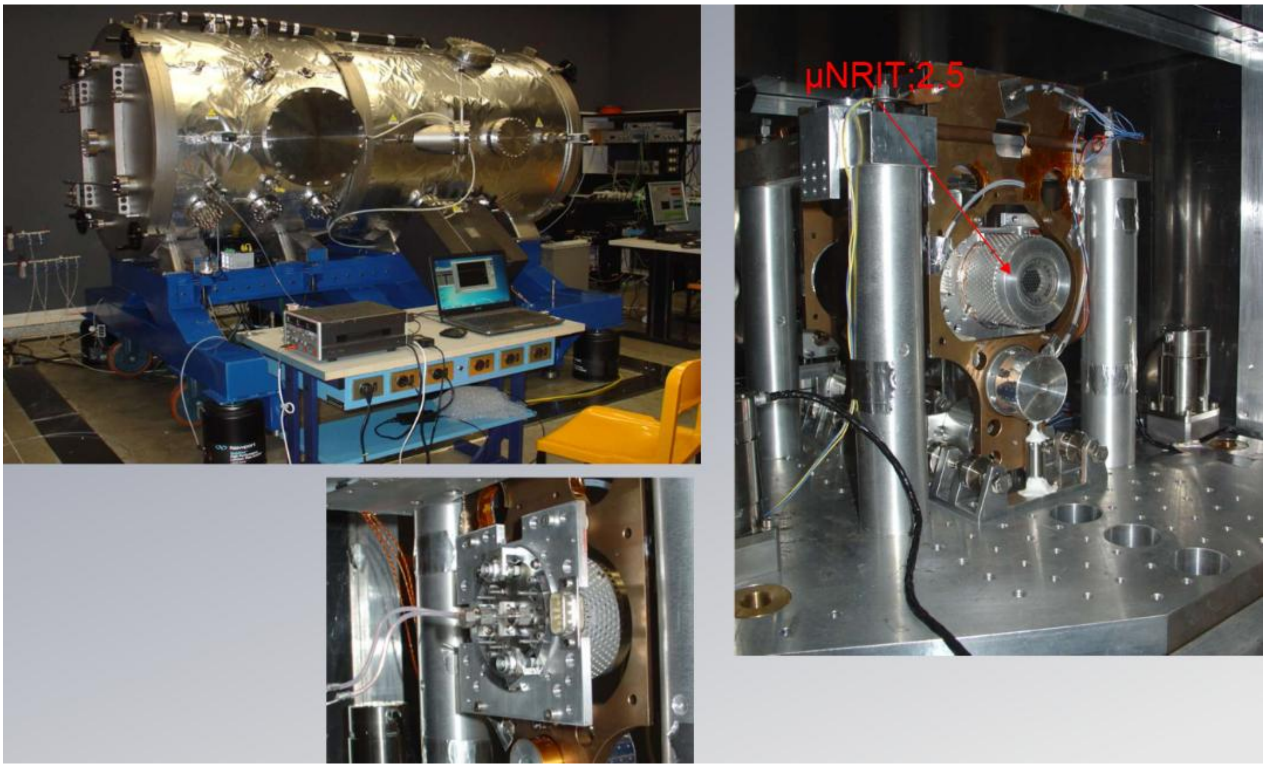

Figure 6 – High vacuum test stand (left) and two photos of the µN RIT-2.5 engine on the nano-balance facility of Thales Alenia Space for direct thrust measurements

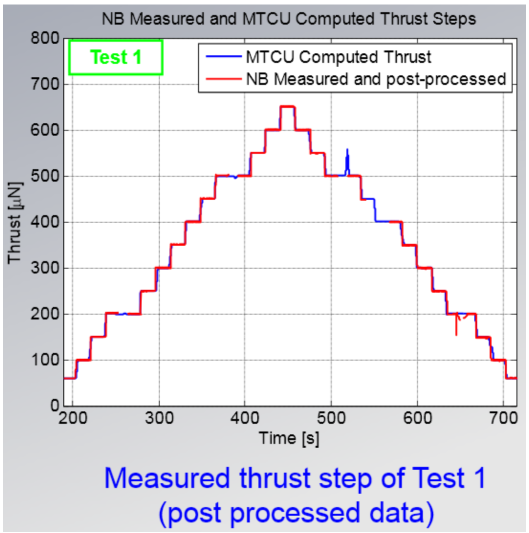

Figure 7 – Directly measured and post-processed thrust steps of the µN RIT-2.5 in the Nano-balance Facility and for comparison the data computed by the MTCU electronics

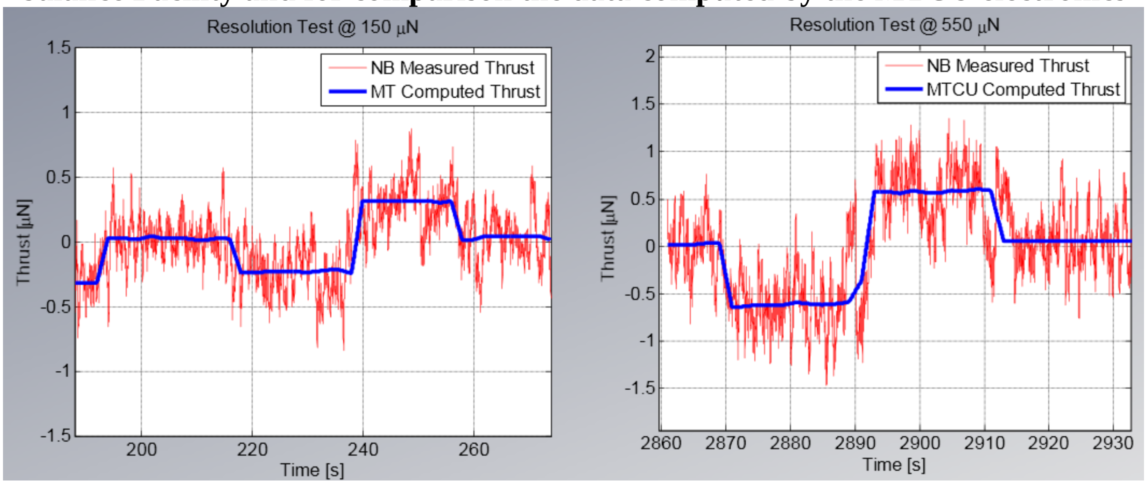

Figure 8 - Thrust resolution of µN RIT-2.5 in Thales Alenia's nano-balance at 150 µN and 550 µN of produced thrust; compare the directly measured thrust deviations with the computed averaged-out differences

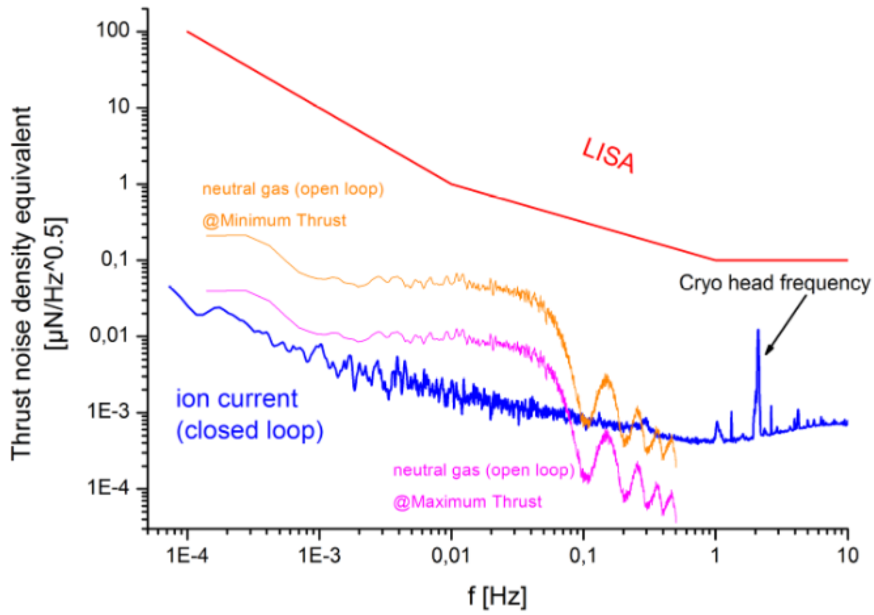

Figure 9 – Thrust noise density of µN RIT-2.5 vs. frequency f and LISA's requirement

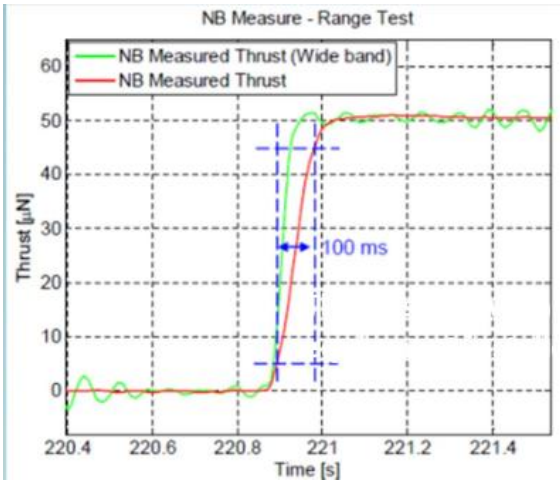

Figure 10 – Thrust rise time of µN RIT-2.5 measured in Thales Alenia's nano-balance

Conclusion and Outlook

- A 2.5 cm ionizer diam micro-thruster of Giessen University «µN RIT-2.5» was tested on a nano-balance of Thales Alenia. It showed good thrusting performance data.
- Thus, ESA/ESTEC placed a new contract at Giessen to build an engineering model of RIT-microthruster aiming towards a flight test, too.

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