Radio Frequency Ion Thrusters Operated with Non-Conventional Propellants

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Summary

By European Space Agency (ESA) subcontract, the University of Giessen investigated a 10 cm diameter Radio Frequency (RF) ion thruster RIT-10 operated with atmospheric gases. Such «RAM-EPs» will be used for air drag compensation of very low orbit satellites which take the propellant from the ambience. The performance tests have been carried out in the large Giessen test facility «Jumbo» with Nitrogen, Oxygen, and with a mixture of both, without and finally with 10 % of Xenon additive. The discharge characteristics showed the known graphs. Also in accordance with theory, the generated thrust at a given beam current was about a half compared with xenon operation. Maximum thrust was found to be 8 mN. A 500 hours endurance test showed no degradation effects.

Keywords

radio frequency ion thruster; test power supply; flow control unit; thrust; efficiency; discharge characteristics

Introduction

The data resolution of scientific satellites, measuring e.g. the gravity field of the Earth or ocean circulations, increases with decreasing flight altitude. Unfortunately, also the atmospheric density and consequently the air drag increases too, and below about 250 km of altitude permanent drag compensation becomes inevitable.

On the ESA’s satellite «GOCE», two small ion thrusters of the QinetiQ T-5 type demonstrated successfully precise drag compensation (Figure 1). However they took the Xenon propellant on board which limits the mission lifetime.

Figure 1 - ESA's low-orbit scientific satellite GOCE with ion thrusters for air drag compensation

Obviously, the mission duration can be theoretically unlimited if the environmental atmospheric gas is used as propellant. Such RAM electric propulsion engine collects the N_2, O, and O_2 particles, stores and eventually compresses them and feeds them into the ionizer.

So, ESA placed a related research contract at ALTA, Italy, with a subcontract given to Giessen University. Hereby, ALTA run an own small SPT motor with nitrogen and oxygen, whereas Giessen used its rf-engine RIT-10 for the same task. As the rf-ionizer has no discharge electrodes and RIT engines have already been operated even with pure oxygen, no problems were feared in the latter case.

Experimental Set Up

Three standard 10 cm rf-engines RIT-10 of Giessen University and EADS Astrium Space Transportation were already successfully flown on the ESA's satellites «EURECA» and «ARTEMIS» (Figure 2, left). Each thruster produced 15 mN at 234 mA of the Xe^+ current and 1.5 kV of positive high voltage.

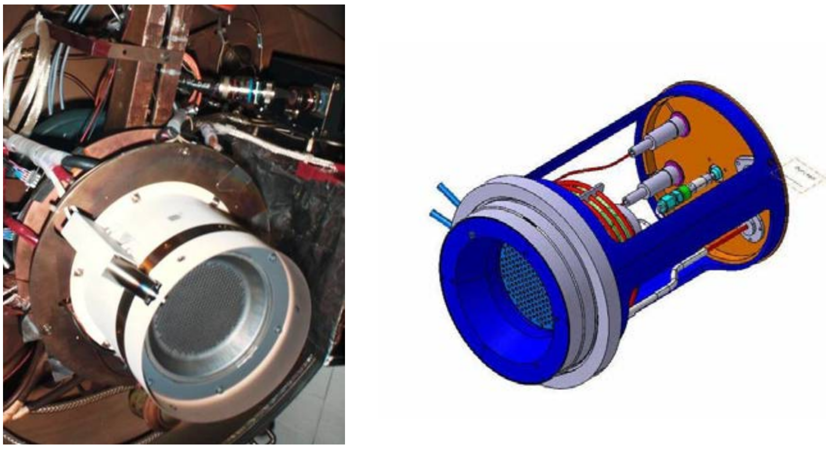

Figure 2 – RIT-10 Flight Design (left) and MAI Experimental Thruster (right)

For the RAM variant, a breadboard RIT-10 has been built (Figure 2, right) with two modifications:

– 1st – A titanium accelerator grid must be used because oxygen corrodes the graphite one by a plasma-chemical process;

– 2nd – Due to the lower ionization cross section of N_2 and O_2 (compared with Xenon), higher RF-discharge power is needed. Therefore, a water cooling system has been installed for the tests.

Figure 3 shows the test power supply. Figure 4 represents the propellant feed system. Following the ESA/ESTEC specification, the RAM RIT-10 should be operated first with xenon, then with nitrogen, after that with oxygen and finally with mixtures.

Figure 5 shows the RAM-engine mounted on the thrust balance of the large Giessen facility «Jumbo». This high-vacuum test stand has a chamber volume of 30 m^3 and a cryo-pumping speed of 100,000 l/s for Xenon. Unfortunately, the pumping speed decreases for air to about one tenth of it. So, the turbo-molecular pumps had to assist the cryo-pumping.

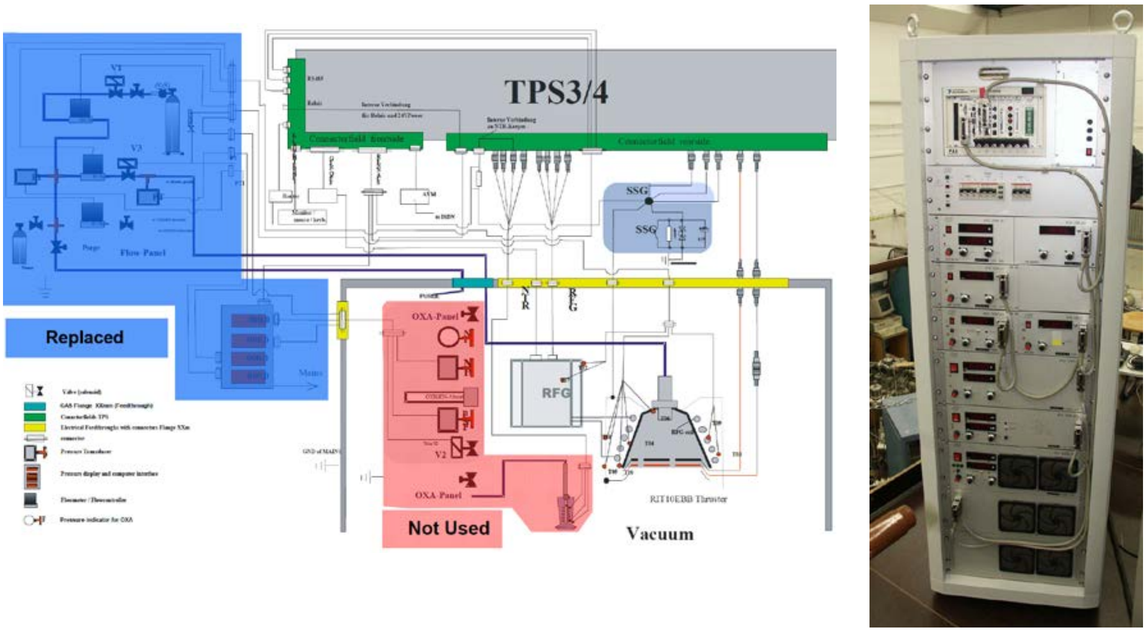

Figure 3 – Test power supply used for RAM RIT-10 testing at Giessen

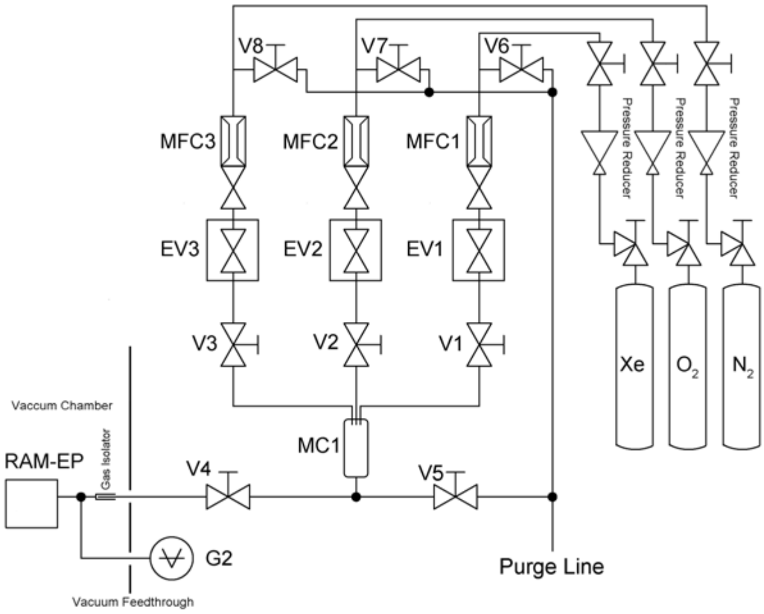

Figure 4 - Flow control unit used for RAM RIT-10 testing at Giessen

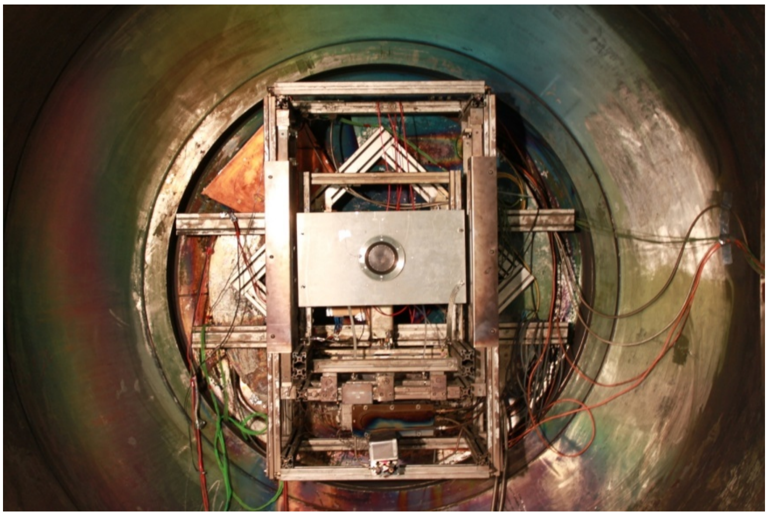

Figure 5 - RAM RIT-10 thruster mounted at the thrust balance of the 30 m^3 vacuum test facility JUMBO at Giessen University

Test Results

The preliminary tests with pure gases (Xenon, then Nitrogen, finally Oxygen) yielded no surprising effects:

- As the thrust is proportional to the square root of the ion masses, atmospheric gases produce only half thrust levels at the same beam currents and voltages compared with Xenon.
- As a consequence of the minor ionization cross section, Nitrogen and Oxygen need significantly higher RF-power levels and propellant flow rates than Xenon if the same beam current should be generated.
- Whereas Nitrogen seems not to be quantitatively dissociated in an RF-discharge (due to the strong molecular binding), both atomic and molecular Oxygen ions appear and the ratio of O^+/O_2^+ depends on the RF-power. So, at a given beam current, the thrust may change with the discharge conditions.

Following the tests with the three pure gases, two mixtures have been investigated:

- 1st A Nitrogen-Oxygen mixture like in an orbit altitude of 200 km was used; the atmospheric model yields 55.95 % N_2 + 44.05 % O_2 (including the dissociated molecules).
- 2nd The same N_2/O_2 ratio but with 10 % of Xenon as support gas was used.

Figures 6 and 7 show for both cases the discharge characteristics and the total power consumption vs. the total propellant flow rate, respectively. Parameters in both graphs are the obtained beam current and the generated thrust, respectively. We see:

- The maximum applied RF-power was around 275 W. A propellant flow of about 8 sccm was sufficient for all cases.
- The maximum generated thrust was nearly 8 mN at 234 mA of beam current.

- For the maximum thrust (with xenon additive), a parameter couple of 154 W/7 sccm seems to be optimal which gives ion production costs of about 660 eV/ion and an electric efficiency of 69.5 %. However, the total power input of the thruster (without neutralizer) would exceed in this case the ESA/ESTEC limit (450 W) by about 50 W.
- In the above mentioned case, the propellant support of 10% xenon saves about 22 W of the RF-power which means a benefit of 14 %. Related to the total thruster power consumption, however, this benefit shrinks to about 4 %. Consequently, one may renounce to take a xenon additive on board low orbit satellites.

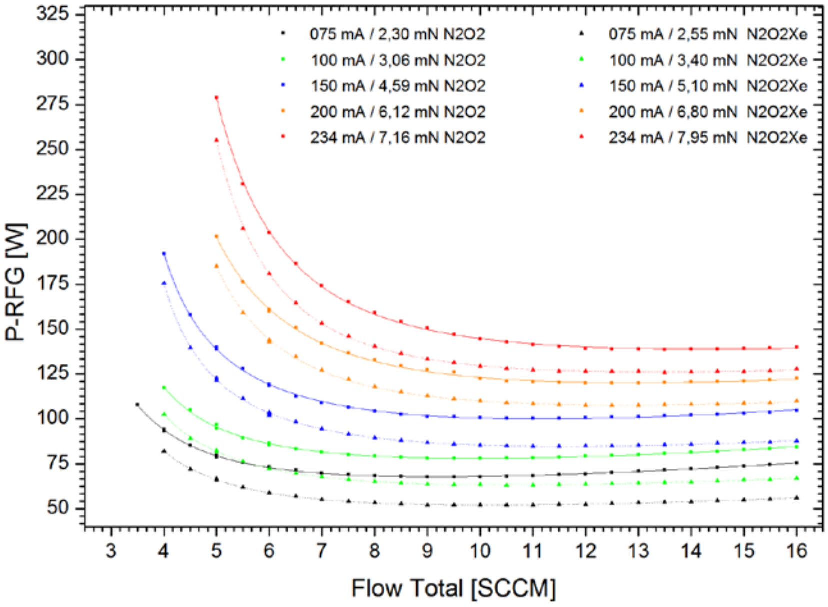

Figure 6 - Discharge characteristics of RAM RIT-10 operated with atmospheric gas, with and without 10 % Xenon additive (RF-power vs. propellant flow rate for different thrust levels)

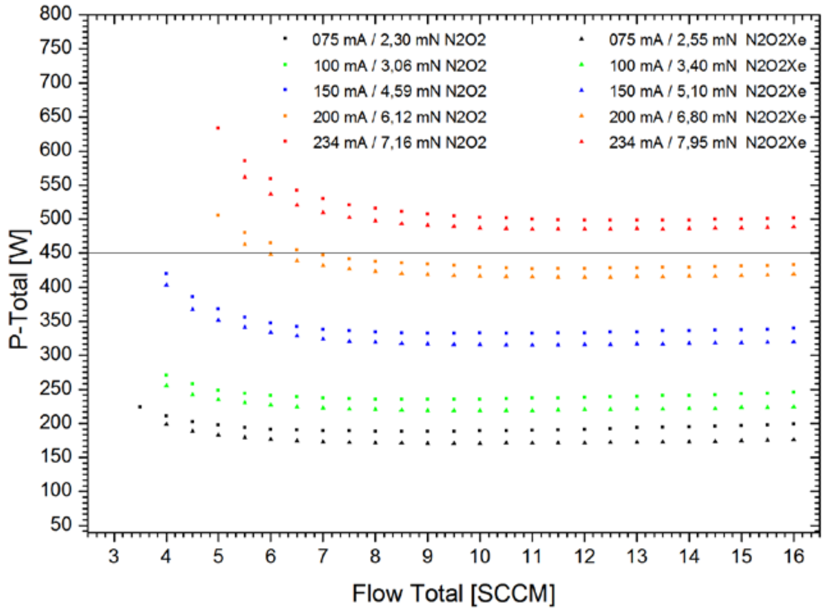

Figure 7 - Performance diagram of RAM RIT-10 operated with atmospheric gas, with and without 10 % Xenon additive (thruster power vs. propellant consumption for different thrust levels)

Duration Tests

Following the performance mapping experiments, the RAM RIT-10 was continuously operated for 500 hrs. The first mentioned gas mixture (without xenon) was used. The following table (see Table 1) gives operational data.

Table 1

Operational Data

Propellant	55.95% N_2 + 44.05% O_2
RF-power	112.5 W
Propellant flow rate	6.5 sccm
Positive high voltage (screen grid)	1500 V
Negative high voltage (accel. grid)	600 V
Beam current	150 mA

No functional problems occurred during the duration test. The discharge keeps stable. Grid erosion measurements were performed to determine eventual erosion. For that, 16 accelerator holes were measured optically, i.e. by microscope (Figure 8, left).

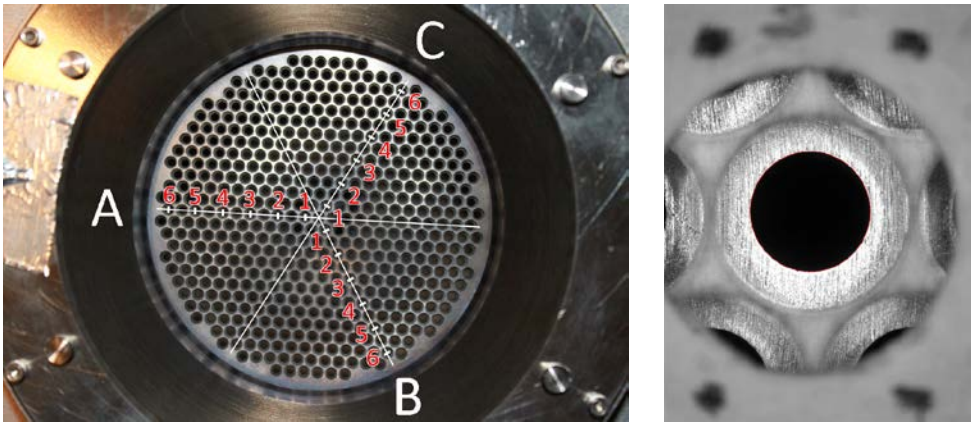

Figure 8 – Grid system of RAM RIT-10 (left) and an enlarged extraction hole after 500 hrs of a duration test (right)

The hole diameters did not change (within an accuracy of 0.01 mm) compared to the baseline measurement and the start of the endurance test. However, some erosion patterns appeared on the upstream face of the accel grid due to the not yet optimized ion optics for N_2/O_2 (Figure 8, right).

Conclusion and Outlook

- Satellites in very low Earth orbits need a permanent drag compensation which could be done by rf-ion thrusters that take their propellant from the surrounding atmosphere.
- The tested RAM RIT-10 breadboard engine worked with a nitrogen-oxygen mixture very well and without problems. A 500 hours duration test showed no degradation effects. An addition of xenon, which must be taken onboard the satellite, is not necessary.

- Due to the lower atomic mass and the smaller ionization cross section, air breathing ion engines generate less thrust and consume more power and propellant than conventional xenon thrusters. In accordance with theory, the performance mapping of RAM RIT-10 showed that.
- The R&D work should be continued with the focus on an optimization of the discharge vessel and the grid optics for atmospheric gases. Furthermore, plasma and beam diagnostics including mass spectrometry as well as an extended lifetime test (> 2000 hours) should be done.

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