State-of-the-Art of Radio-Frequency Ion Thrusters

K. H. Groh* and H. W. Loeb†
Giessen University, Giessen D-6300, Germany

Since 1960, a family of radio-frequency ion thrusters (RIT) with ionizer diameters from 4 to 35 cm has been studied, developed, and tested at Giessen University. The 10-cm North-South-Stationkeeping engine RIT 10, with 10 mN of nominal thrust, has been industrialized since 1970 and fully ground qualified with mercury through 1980. This thruster has been redesigned for xenon as the propellant since 1983 envisaging a flight test onboard the European Retrievable Carrier EURECA in the year 1991. A chance for an operational application of the RIT 10 system is given onboard the European Space Agency satellite SAT 2, which is planned to be launched in the early 1990s. Because of the grown masses of satellites and with it the higher thrust requirements for North-South-Stationkeeping, a laboratory prototype of a scaled-up engine, the RIT 15, is presently under performance mapping aiming at a thrust level of 50 mN. For primary electric propulsion a large prototype engine, RIT 35, has been developed. After starting in 1984 with performance mapping using a flat grid extraction system and mercury as the propellant, the thruster has been modified for inert gases as argon and xenon. Finally, a dished grid extraction system has been fabricated and tested on the RIT 35 thruster.

Introduction

AFTER nearly three decades of worldwide research and development programs, qualification procedures, and also several space tests, the low-thrust but high-energetic electric propulsion (EP) systems are now ready for application in space. In the domains of orbit control of geosynchronous satellites, requiring thrust levels of about 50 mN, and of spacecraft propulsion, requiring a thrust of about 1 N, the EP systems show significant payload and delta-v advantages over all chemical rockets because of their high exhaust velocities in the order of 50 km/s, which means a 10 times higher specific impulse in the order of 3000 s.

Among the two classes of electric propulsion, the plasma thruster and the ion drive, the latter seems to be much more favorable for the mentioned applications because of its much higher lifetime (about 10,000 h are proved) and better total efficiencies (50–80%). Also, the thermal control can be performed, in general, rather easily. The disadvantages of the ion thrusters are the more complicated thruster design and power supply and control circuits and the lower thrust and beam densities compared with the plasma engines.

The modular concept of the ion propulsion system (thruster, power supply, and propellant module) avoids problems of integration of the propulsion system into the spacecraft. The generation of the required high beam voltages (1–4 kV) and of the beam neutralization by electrons from a plasma bridge neutralizer are state-of-the-art.

The research, development, and qualification activities at the 1st Institute of Physics at Giessen University followed all these generally outlined trends. Because of some conceptual advantages, the radio-frequency ion source type has been favored from the beginning, working with an electrodeless discharge rather than the dc-bombardment systems preferred elsewhere.

Research, Development, and Qualification Programs of Ion Engines at Giessen University

In 1960, the development of radio-frequency ion thrusters (RIT) started with a lot of basic experiments at a laboratory device of 8.6-cm ionizer diam. After optimization of the discharge chamber and of the extraction grid geometry and plasma diagnostic analyses, the development and testing of a standardized 10-cm engine, RIT 10, has been initiated and supported by the German Ministry for Research and Technology. The state of a laboratory prototype was reached about 1970.[1,2]

Then, a space company in Munich started the industrialization of the engine with regard to a qualification for an application in space. In 1974, another research company in Stuttgart joined the qualification program and carried out a successful 8150-h lifetime test and more than 2100 operational cycles on three RIT 10 engines.[3]

In 1980, the RIT 10 system, including power supply and control system as well as the mercury tank and feed system, was fully ground qualified and planned to be flown onboard the German TV-Sat, performing North-South-Stationkeeping (NSSK). Because of budgetary and management problems, the previously planned space test had been cancelled.

Then, the European Space Agency (ESA) accepted the RIT assembly, RITA 10, as one of the European EP programs. The RITA 10 has been redesigned for xenon as the propellant and equipped with an updated power processing unit (PPU) and a new digital automatic control unit (DACU) system. From 1986 through 1988, the complete flight hardware was tested successfully in several tests representing different development states in the 30-m^3 vacuum facility in Giessen.

RITA 10 is now ready for the test in space and will be flown onboard the retrievable ESA platform EURECA, which is unfortunately delayed due to the Challenger disaster. At present, the launch is scheduled for April 1992.[4]

Meanwhile, a further opportunity for an application in space is given onboard the European SAT 2 satellite where the electric propulsion system shall be used operationally for NSSK. At present, a RITA 10 unit with simplified power and propellant supplies is prepared for this test.[5]

Since 1968, several student theses dealt with experimental and theoretical rf-discharge diagnostics, especially also with scaling laws[6] and with research and development at plasma bridge neutralizers.[16] Laboratory devices of a scaled-down 4-cm ionizer diam engine RIT 4 as well as of scaled-up thrusters RIT 15, RIT 20, and RIT 35 have been investigated.[7]

During the first half of the 1980s when the NSSK thrust requirements increased, the 15-cm-diam thruster RIT 15, which was already optimized for mercury as the propellant from 1974 to 1976, was redesigned.[8] Recently, a laboratory engine has been manufactured at Giessen and performance was mapped with xenon.

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*Head of Electric Propulsion Section, 1st Institute of Physics.
†Head of Plasma Department, 1st Institute of Physics.

In 1983, when a primary electric propulsion application for primitive bodies mission as multiple asteroid fly-by and/or comet rendezvous became relevant, the 35-cm-diam engine RIT 35, which was investigated already with some interruptions from 1972 to 1980 at Giessen and at Stuttgart, was redesigned.[9,10] Hereby, the RIT 10 qualification experiences were widely adopted. Now, the application of a RIT 35 cluster for the comet nucleus sample return (CNSR) mission is envisaged, which is one of the four ESA cornerstone missions within the program Horizon 2000.[11]

By ESA fundings and industrial subcontracts, the RIT 35 laboratory prototype has been fully performance mapped at Giessen University with mercury, argon, and xenon as propellants.[12] A dished grid extraction system built by a space company in Munich was also tested in the large Giessen test facility.

Mode of Working of the Radio-Frequency Engines: Gas Supply

All ion sources of the RIT family are working with an inductively coupled, electrodeless radio-frequency discharge and with an ion-optically optimized, multihole three-grid extraction system. Besides mercury, the rf-ion thrusters are operated with the inert gases xenon, argon, and krypton. Usually, the propellant is stored in a pressurized tank and fed into the ion source via a pressure reducer, a flow controller, the insulator, and the gas distributors (see Fig. 1). In the case of mercury, the propellant is stored and fed in liquid condition and then vaporized by an electrically heated, fine meshed grid on top of the insulator.

The flow controller measures and adjusts the gas flow rate, which gives together with the atomic or molecular weight the mass flow rate. For basic investigations, an additional vacuum gauge is used sometimes to measure directly the discharge pressure. In the laboratory, commercial available flow controllers are used, but for space application, a special flow control unit has been manufactured by space industry.[4]

The insulator is made of quartz and separates electrically the grounded gas supply system from the gas distributor, which is floating on plasma potential. Its design depends on the applied flow rate. For flows that are not too high, the left branch of the Paschen curve is preferable, which means low pressure and small distances, but for very high flows, the right branch must be used.

The gas distributor of the rf thruster acts also as the extraction anode, which has to collect the number of electrons equivalent to the number of beam ions being extracted. Usually, it is made from stainless steel and connected to the positive high-voltage power supply (see also Fig. 1).

Radio-Frequency Discharge

The propellant is ionized by an inductively coupled, annular, electrodeless, self-sustaining radio-frequency discharge.[13] For this reason, the ionizer vessel is made of quartz and placed inside the induction coil, which is connected to the rf generator. The magnetic field of the coil penetrates the discharge chamber and induces an azimuthal electrical eddy field.

This field, which is influenced by the skin effect and inhomogeneities, accelerates the discharge electrons to gather the energy for ionization. The energy accumulation is affected by the collision statistics. That means, the discharge pressure, the rf frequency, and the ionizer dimensions must be adapted to each other.

The rf discharge produces a dense, nonisothermal plasma, which is the ion reservoir for beam extraction. The plasma density depends on the incoupled rf power and reaches some 10^{11} ions and electrons per cm^3. The plasma density decreases toward the ionizer walls, whereas the electron temperature increases from the axis toward the walls and reaches some 10,000 K.

The extractable ion current depends on both the plasma density and the electron temperature. Because of their increase and decrease, the profile of the extractable ion current is more or less flat.

The specific rf power requirements are ruled by the rf discharge carrier and energy balance. The carrier balance is char-

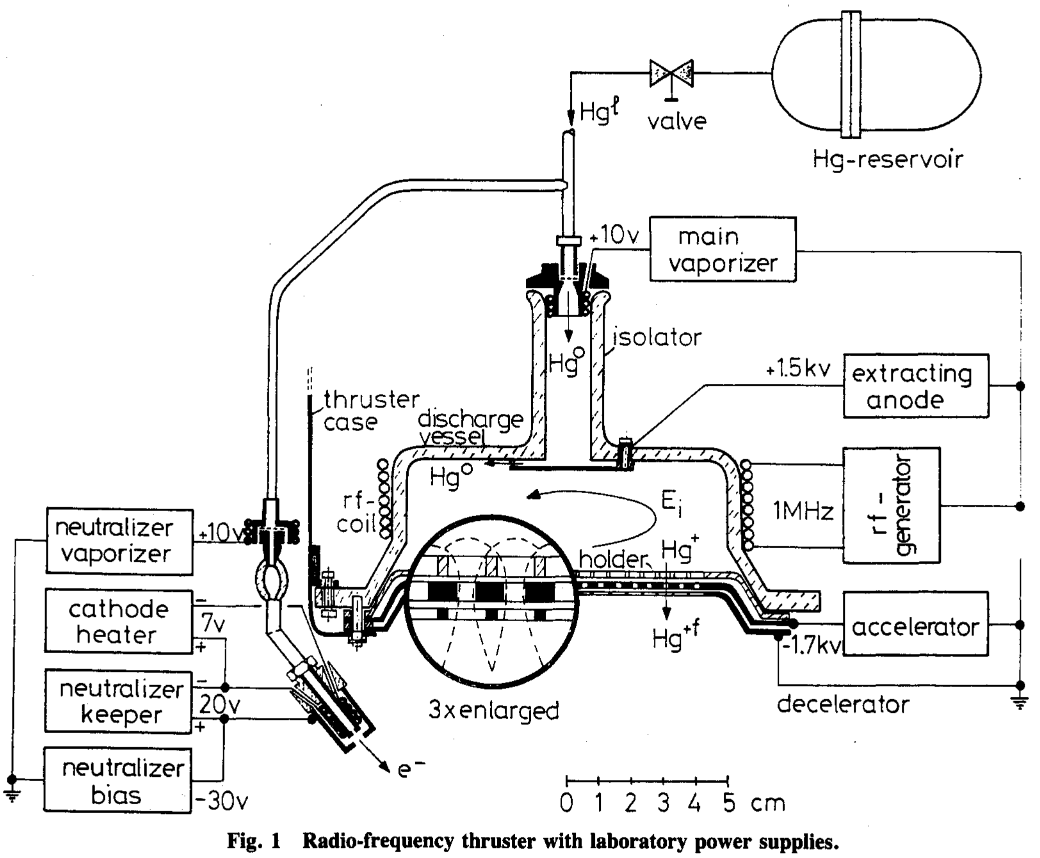

Fig. 1 Radio-frequency thruster with laboratory power supplies.

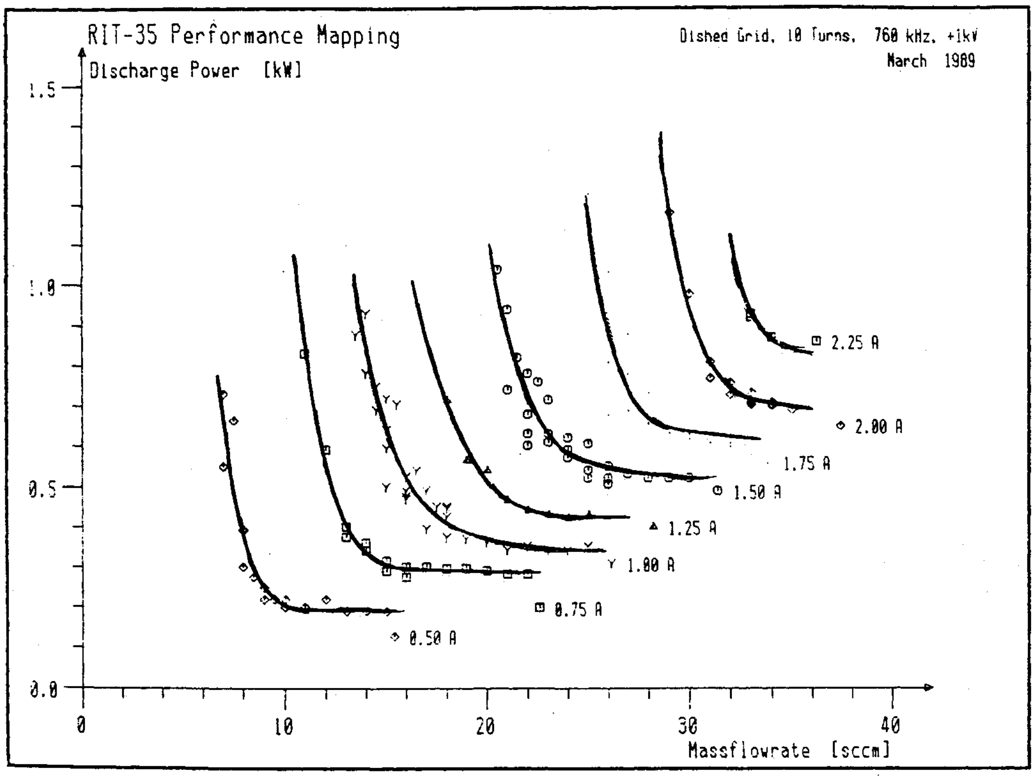

Fig. 2 35-cm radio-frequency thruster, obtained with xenon and the dished grid system.

acterized by the ion production rate on one side and by the ion extraction together with all recombination losses on the other side. The energy balance equalizes the rf power, absorbed by the plasma, to the ionization energy, the preacceleration of the ions to the walls, and all losses for excitation, dissociation and elastic collisions. Both balances are governed by two basic discharge parameters, the rf power and the discharge pressure or the mass flow rate.

Figure 2 gives an example of these basic discharge curves for the big RIT 35 rf thruster. The curves demonstrate that the rf power, which is necessary to maintain the discharge, starts increasing if the mass flow rate is lowered. The curves for different beam currents are shifted against each other but have the same shape.

Radio-Frequency Ionizer

The rf ionizer consists of only two main parts, the rf generator with the induction coil and the ionizer vessel. The rf generator, an oscillator with an rf-amplifier stage, provides the required power via a matchbox to the induction coil. The matchbox cares for an efficient coupling of the rf power into the plasma by matching the load impedance to the generator output impedance.

Of course, the required discharge power increases with parameters like engine size and ion beam current. Experiments with all rf engines demonstrated a strong linear relation between the rf power and the beam current (as graphed in Fig. 3).

The generator frequency is usually about 1 MHz for the smaller engines and about 0.75 MHz for the bigger ones, as in the RIT 35. Lower frequencies induce lower eddy current losses in the grids and the structure and, therefore, they are preferable.

The induction coil geometry and number of turns has been optimized, too, with respect to Ohms losses, rf matching, etc. Normally, silvered copper wires or tubes are used for the fabrication of the coils.

The discharge vessel length is another parameter to be considered. In agreement with the theory,[13] the optimum length-to-diameter ratio increases with decreasing mass of propellant. Figure 4 gives an example for that by means of the data of the RIT family engines operated with mercury, xenon, argon, nitrogen, and oxygen.

As the rf engines are working with a self-sustaining discharge, in which all the ionizing electrons have been produced by previous collision processes, a discharge igniter must be used. For that, the plasma bridge neutralizer is taken injecting its electrons into the discharge chamber for main discharge starting.

Since the discharge is sustained by energy coupled in through the ionizer walls, a change in the properties of the wall will change the performance of the thruster. It has been observed during the lifetime test that sputtered carbon from the accelerator grid formed a layer on the walls requiring finally more power for the same beam current. During the 8000-h test, the power increase was in the order of 10%.

Ion Extraction and Beam Formation

The ions are extracted from the plasma, accelerated and focused to the beam by a multihole three-grid system.[14] The first grid, called plasma holder, is in contact with the plasma and takes its potential, usually a positive high voltage, which may be applied to the plasma holder itself or to the gas distributor. The quasineutrality of the plasma is kept by collecting a beam-equivalent number of electrons at the extraction anode.

The second grid, the accelerator, is on negative high voltage. The sum of the positive and the negative potential is the extraction voltage, which is responsible for the beam formation.

The third grid, the decelerator, is at ground potential. It decelerates the ions that finally the exhaust velocity of the ion beam corresponds to the applied positive high voltage. The decelerator grid is closed, which means that it is extended over the total beam cross section and has the same number of borings than the other grids. In this way, the accelerator grid is protected against impingement by ions that are created

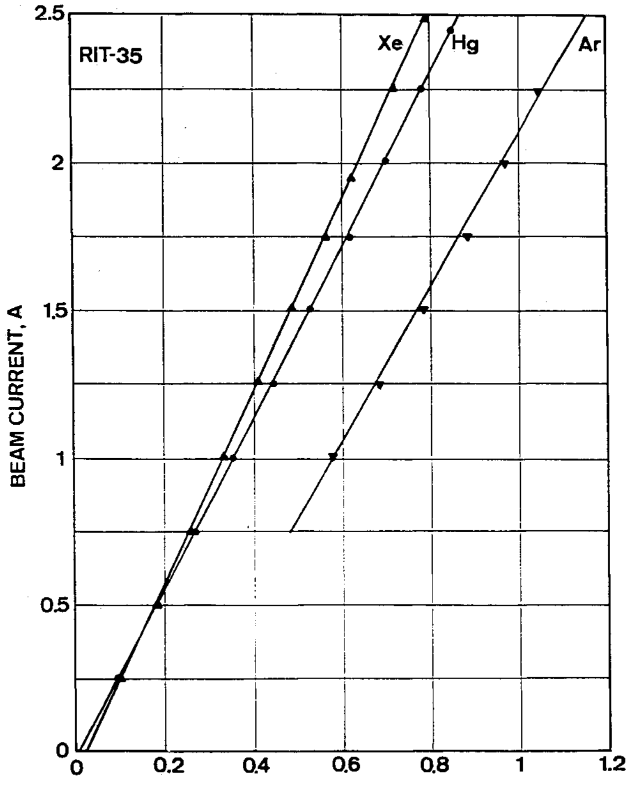

Fig. 3 Ion beam current vs discharge power for different propellants—mercury, argon, and xenon.

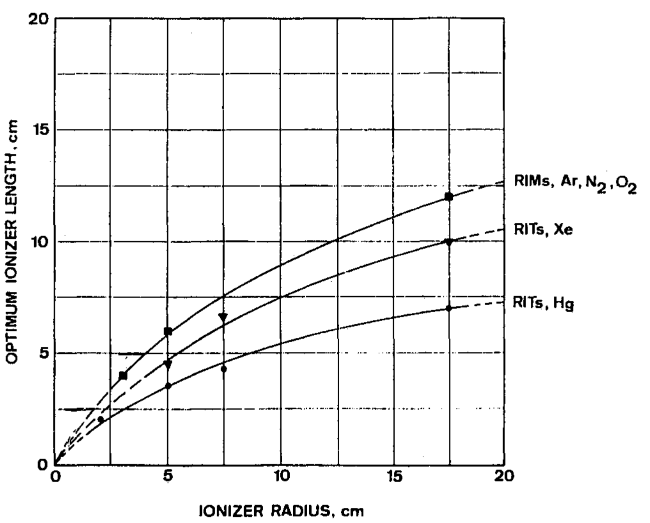

Fig. 4 Optimum discharge vessel length vs the engine size.

outside the grid system either by the neutralizer plasma or by collisions in the beam with neutrals. In this regard, the three-grid system is superior to the two-grid version avoiding sputtering of the accelerator grid, which has been found after life testing of such systems.

The first rf engines like the RIT 10, which has been developed in Giessen, which was industrialized and finally ground qualified, uses a plasma holder made of quartz. The larger engines use a metal holder due to the higher mechanical stability. For a holder material, Invar is preferred because of its low thermal expansion even under high thermal stress. The accelerator grid of all rf thrusters is made of graphite because of its low sputtering rate under ion bombardment. It is a disc of graphite that is kept in a stainless steel ring. The decelerator grid is manufactured also from Invar, but for laboratory engines, also stainless steel has been used successfully.

The grid and hole geometry have been optimized during the first years of RIT development. Usually, the hole diameters of the plasma holder and the decelerator grid are the same, namely 4 mm, but the accelerator grid boring is only 2 mm in order to reduce the neutral gas losses. The typical grid interspace is about 1 mm. The number of extraction holes varies with the thruster size and starts with 253 for the small RIT 10 engine up to 4267 for the RIT 35 dished grid system. The typical open area ratio is about 40% for the quartz plasma holder with 1-mm spacing between the holes and about 55% for the metal plasma holder with a spacing of 0.5 mm.

The thermal load of the grid system is caused by the heat of the discharge, by eddy currents, and by the accelerator grid drain current. In the case of the small RIT 10, the thermal load is no problem. For the larger engines, one has to take care that the grid alignment does not change during operation. Therefore, a dished grid system has been manufactured for the big RIT 35 thruster that is able to keep alignment and spacing exactly.[15] It uses graphite, and Invar for the holder. The accelerator and the decelerator grid has 4228 extraction holes. The dishing radius of curvature is 1.5 m.

The beam profile and beam divergence of rf engines depend mainly on the plasma density distribution and the accelerator-decelerator ratio. Beam diagnostic measurements performed at a mercury RIT 10 thruster demonstrated good profile data and a typical divergence of about 10-deg half angle for a ion beam voltage of 1.5 kV. Approximately 95% of the ion beam is included in the 10-deg half angle envelope.

For space applications, ion thrusters must be equipped with a neutralizer in order to keep the spacecraft electrically neutral. A standard hollow cathode plasma bridge neutralizer[16] is used with an electron emission exceeding 1 A. These neutralizers have been developed in Giessen, but since 1978, they are manufactured by an industrial company. Also, the propellant has been changed from mercury to inert gases. The standard neutralizers are also used in the RIT 15 and RIT 35 programs. For the big thruster, two or three are foreseen for redundancy.

Power Supply and Control

The rf-engines requirements to power supplies and control systems are rather simple. To sustain the rf discharge, only the rf generator is necessary of course together with the propellant supply. The ion extraction and acceleration is performed by a positive and a negative high-voltage supply. Finally, the plasma bridge neutralizer needs its power supply consisting of two low-voltage converters for the cathode heater and the neutralizer discharge. All power supplies are on ground potential, which avoids difficult insulations.

The ion beam current and with it the thrust level is controlled easily via the rf power only. If the efficiencies shall be kept at its optimum, the mass flow rate to the thruster may be adapted, too. Besides the rather simple and rugged mechanical setup, these modest electronic and control requirements provide high reliability and lifetime and present the conceptual advantage of the rf thrusters over all dc-discharge devices.

Radio-Frequency Thruster Hardware

North-South-Stationkeeping Thrusters RIT 10 and RIT 15

The NSSK of geosynchronous satellites over a period of at least 10 years is one of the most attractive applications of EP systems. Mass savings between 10 and 15% of the satellite mass can be achieved by EP, which would provide significant commercial benefits.

As pointed out already earlier, the 10-cm engine RIT 10 has been developed and ground qualified for these purposes. When ESA took the decision to fly the system onboard EURECA, safety aspects associated with a possible contam-

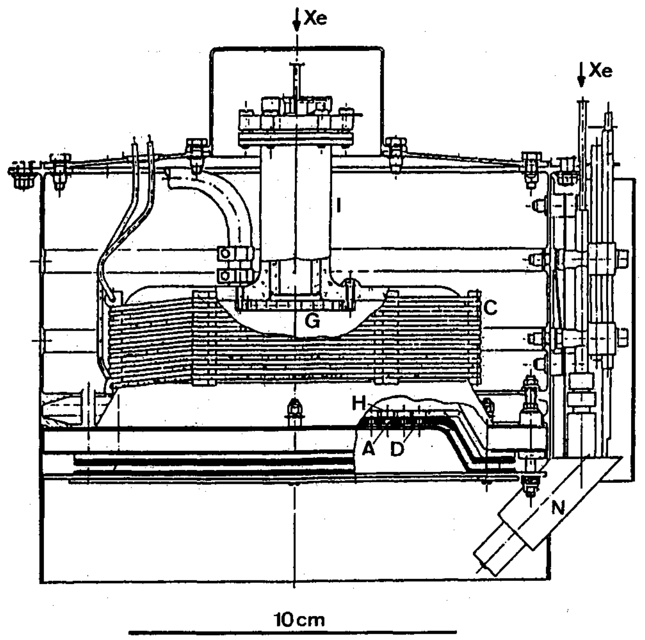

Fig. 5 10-cm NSSK engine RITA 10 to be flown onboard EURECA in 1991.

ination by mercury led to the need to replace mercury by xenon as the propellant.

The changes of the thruster were trifling; the main vaporizer and the neutralizer vaporizer were removed. A flow control unit with xenon tank, pressure reducer, and flow controller was added. Figure 5 shows a drawing of the RIT 10 XE engine. It is 15.5 cm in diam, 16 cm in length, and weighs 1.0 kg[4].

Two basic thruster data, namely, the nominal thrust of 10 mN and the beam voltage of 1.5 kV, remained unchanged compared with the Hg engine. Therefore, the xenon version needs somewhat higher beam curent and power, whereas the consumption of the propellant mass is correspondingly lower. More detailed data are given in Table 1. Furthermore, the comparison of the two first columns of Table 1 demonstrate that the xenon thruster has a 10% higher exhaust velocity but a somewhat lower overall efficiency than the Hg motor.

In general, the RITA 10 flight hardware has a throttling range from 5 to 10 mN (up to 13 mN have been proved in ground tests, limited by the power supplies) at a power input from the EURECA mainbus of 270–440 W. The dissipation power will be radiated into space and drained by EURACA's cooling system half and half.

Figure 6 shows the complete RITA 10 flight experiment package mounted on a 70 × 70 cm equipment support panel. The system consists of the following components[17]: the propulsion unit (PU) with thruster, neutralizer, and its mounting structure; the rf-generator box (RFG); the power supply unit (PSU), which is connected to the mainbus and the DACU; and the propellant feed system, consisting of a 50-bar xenon tank, a pressure reducer, and the flow control unit (FCU). Together with 3.5 kg of xenon, cabling and fixations (1.5 kg), and a margin of 2 kg, the complete experiment will weigh 35 kg. This rather high weight is caused mainly by the heavy tank (diving bottle) and the structure of the electronic boxes, which are not optimized with respect to weight.

For a real NSSK mission, e.g., for a 1.5-ton geosynchronous satellite, the dry mass of 4 RITA 10 electric propulsion units will be kept within 50 kg in total. For the flight test onboard EURECA, a microprocessor-based DACU had to be developed because the contact to ground will be less than 30 min per day; thus, RITA must be operated automatically and all data must be stored onboard and transmitted to the ground during the short contact periods.

It must be pointed out that this DACU system developed for RITA 10 can be used in principle for all other types of radio-frequency ion thrusters but the power supplies have to be adapted to the thruster size, of course.

In 1987 and 1988, three successful test runs of the complete flight hardware in the large test facility at Giessen were carried out. After an experiment integration and a vacuum function and qualification test, a final acceptance test of the complete flight hardware followed at end of 1988.

Table 1 Characteristic data of the 10- and 15-cm ionizer diameter NSSK thrusters RIT 10 and RIT 15 and of the primary propulsion engine RIT 35, all are operated with mercury and xenon; the data for the RIT 15 LP and the RIT 35 LP contain scheduled values

	RIT-10	RIT-10	RIT-10	RIT-15	RIT-15	RIT-15 LP	RIT-35	RIT-35	RIT-35 LP
Propellant	Hg	Xe	Xe	Hg	Xe	Xe	Hg	Xe	Xe
Thruster diameter, cm		15.5			22			45	
Thruster mass, kg		1.0			2.0			9.0	
Discharge vessel length, cm	3.5	4.5	4.5	4.2	7.5	7	7	10	10
Number of extraction holes		253		511	511	571	4228	4228	4267
rf-Discharge power, W	86	90	230	150	217	325	890	690	1250
Discharge pressure, 10^{-4} Torr	2.3	3.9	5.0	1.8	3.6	5.3	1.6	1.8	3.0
Extraction voltage, kV	3.2	3.0	3.75	3.3	3.3	4.0	4.1	3.2	5.75
Beam voltage, kV		1.5		1.5	1.5	2.0	2.5	1.0	4.0
Beam current, mA	127	156	386	250	450	670	2450	1950	4000
Drain current, mA	2	2	11	4	15	20	60	85	80
Total mass flow, mg/s	0.33	0.30	0.68	0.64	0.79	1.17	5.87	3.32	6.63
Ion velocity, km/s	38.4	47.4	47.4	38.4	47.4	55.0	49.4	39.3	77.3
Beam velocity, km/s	30.7	33.0	36.5	31.4	36.6	42.7	42.8	31.5	63.4
Beam power, W	196	240	598	388	698	1374	6190	2050	16200
Thruster power input, W	293	340	865	555	958	1767	7330	2965	17830
PCU power input, W	375	440	—	—	—	—	—	—	—
Electric efficiency, %	67.0	70.6	69.1	69.8	72.9	77.7	84.4	69.1	90.9
Mass efficiency, %	80.0	69.6	77.1	81.7	77.2	77.7	86.8	80.0	82.0
Total efficiency, %	53.1	48.6	52.7	56.4	55.7	59.8	72.5	54.7	73.8
Thrust, mN	10	10	25	20	29	50	250	104	419
Thrust range, mN	5–10	5–10	10–25	10–20	10–30	25–50	50–250	50–200	100–400

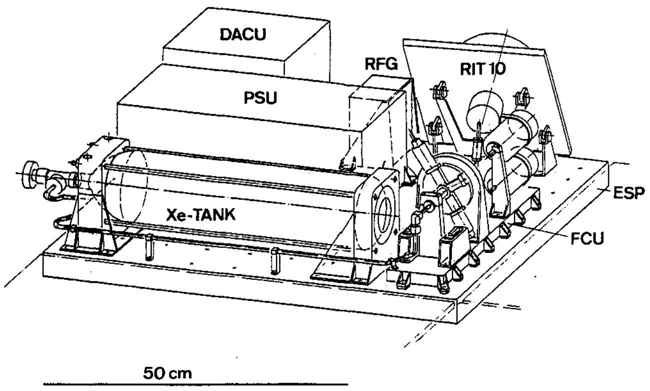

Fig. 6 Experiment arrangement of RITA 10 on the EURECA equipment support panel.

This RITA 10 package will be one of 14 experiments on the free-flying retrievable platform EURECA, which shall be launched by the Space Shuttle probably in 1991. After a six month mission in a 500-km orbit, it will be retrieved and returned to Earth by another shuttle flight.

In the course of the EURECA mission, the RITA experiment will be operated for at least 1500 h at different thrust levels. Operational experience shall be gained and possible interactions with the spacecraft evaluated. After in-flight demonstration of operation, lifetime and reliability, the recovery of EURECA will provide the unique chance of a past-flight inspection, too. Finally, "the test should demonstrate the mature technology of the RITA system and open the way for its operational use."[4]

In order to meet the grown NSSK thrust requirement of future heavy satellites, the RIT 10 xenon engine has been operated at Giessen also with augmented thrust levels up to 25 mN[18]; this limit was given only by the available rf generator and the poor pumping speed of the test facility, which was at disposal for that experiment.

In addition, the 10-cm engine has been scaled up to a 15-cm thruster, the RIT 15. Following two laboratory motors running with mercury and xenon, a prototype engine has been manufactured at Giessen by in-house fundings. This RIT 15 LP uses all knowledge and experience gained at the RIT 10 and RIT 15 L programs; the ionizer of the engine is 7 cm in length and the grid system has 571 extraction holes, which enable a 2.25 times higher thrust than the RIT 10 (for the same discharge data). Besides the plasma holder, which is made of titanium, the RIT 10 technique is used widely; e.g., a RIT 10 hollow cathode is used as the RIT 15 plasma bridge neutralizer.

Performance mapping with xenon and other gases is currently done. The maximum thrust obtained up to now is 29 mN for 1.5-kV beam voltage. Using a new, more powerful rf generator, the RIT 15 LP is planned to be operated at thrust levels of about 50 mN.

Primary Propulsion Thruster RIT 35

The field of EP application for advanced primary propulsion missions comprises multiple rendezvous and/or sample return flights to the primitive bodies, like asteroids and comets, Mercury orbits, Mars and Mars-moon sample return, outer planet missions, out-of-the-ecliptic probes, long baseline interferometers, and others.[9–12,19] Also, high-payload cargo missions from low Earth orbit to geosynchronous Earth orbit or round trip flights between a Shuttle orbit and a Moon orbit would be profitable EP scopes.[20]

In 1983, ESA studied a multiple asteroid rendezvous called AGORA[10]; later, a comet nucleus sample return mission[11] got the priority, which again desires an interplanetary electric propulsion module (EPM). In order to get on the primary propulsion hardware and to establish a reliable basis for imminent projects decisions, ESA/ESTEC dropped contracts to study an EPM on the basis of a cluster of 35-cm rf thrusters RIT 35.[21]

As a subcontractor, the University of Giessen built a RIT 35 laboratory prototype deriving benefits from the experience with three Giessen and Stuttgart motors and with the RIT 10 qualification program. From 1985 until January 1987, a 7-cm-long quartz ionizer, a 4228 holes flat grid system, and a RIT 10 neutralizer were used for performance mapping with mercury[22]; three test series were accomplished with ion beams up to 2.45 A and beam voltages up to 2.5 kV. The maximum measured thrust was 250 mN, which was limited by the available positive high-voltage supply unit.

In spring 1987, the RIT 35 engine was modified for testing inert gases. The ionizer vessel was lengthened from 7 to 10 cm, the vaporizers were removed, and the neutralizer was equipped with an oxygen absorber. This absorber turned out necessary since the residual oxygen content of commercial xenon is dangerous to the electron emitting material and leads finally to a malfunction of the neutralizer by poisoning of the electron emitter. Particular attention was drawn to the redesign of the gas distributor to ensure a high flow conductivity. Then, performance mapping was carried out with argon and xenon as the propellants. Figure 7 shows the thruster power input as a function of the mass flow rate for different thrust levels for mercury and xenon.

In autumn 1988, a dished grid system for the RIT 35 motor was ready for testing, which promised a better mechanical stability than the flat grids and keeps its alignment and spacing also under thermal load. After some improvements of the intergrid insulation, it was fixed to the available thruster.

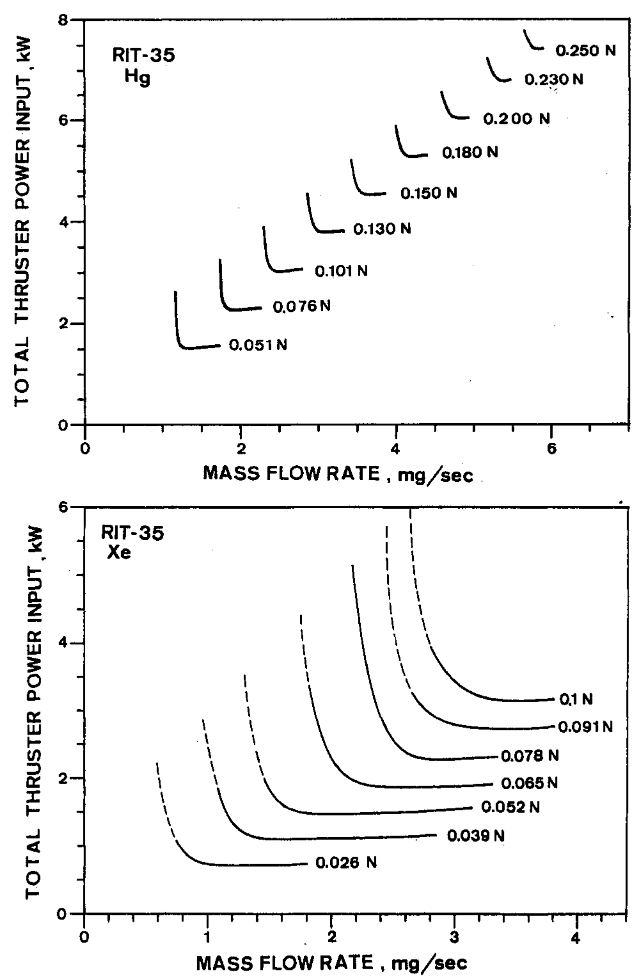

Fig. 7 Total power consumption of the RIT 35 engine for mercury and xenon as a function of the mass flow rate for different thrust levels.

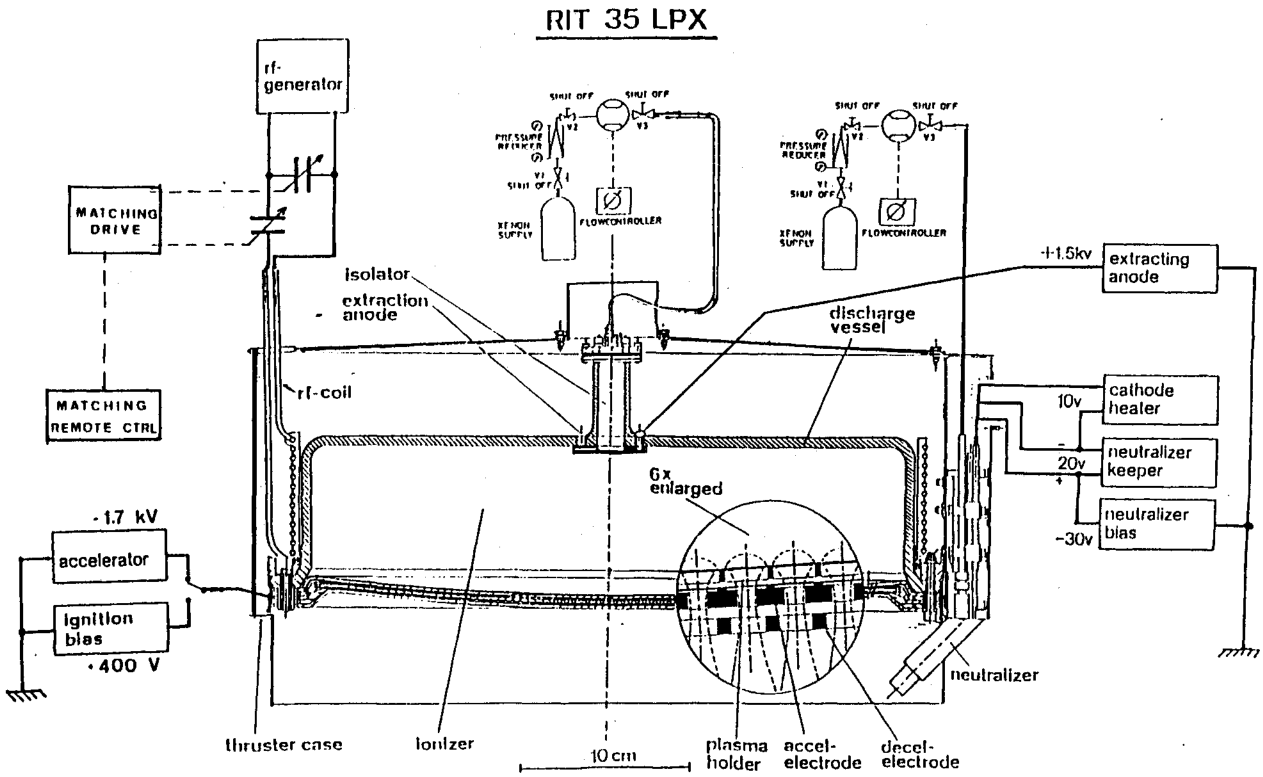

Fig. 8 RIT 35 engine with dished grid system and sketched power and propellant supplies.

Figure 8 is a drawing true to scale of the RIT 35 with dished grid system, gas supply, and laboratory power supply.

The performance mapping was carried out during spring 1989 and demonstrated excellent thruster performance, especially unexpected low drain currents due to the exact alignment of all grids. Recently, the tests were terminated and the data evaluation is under way; thus, more detailed results cannot yet be given here.

To conclude the discussion of the RIT family, their conceptual advantages and disadvantages, as compared with the dc-bombardment competitors, are summarized.

The rf engines advantages are the following:

1) The absence of discharge electrodes guarantees very high reliabilities and long lifetime even at rather high power and thrust levels.

2) The closed decelerator grid protects the accelerator grid against damage by backstreaming ions.

3) The engines are simple and rugged in construction.

4) The power processor and control requirements are more modest because of simple control of the rf discharge and power supplies on ground potential.

The disadvantages of the rf engines are the somewhat lower efficiencies caused by eddy current losses and the higher discharge pressures that are required to sustain the self-sustaining rf discharge.

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