Forty Years of Giessen EP-Activities and the Recent RIT-Microthruster Development

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Abstract

Since the early 60ies, gridded ion thrusters with rf-ionizaton of the propellant (first mercury, lateron xenon) have been designed, built, investigated, optimized, and tested at Giessen University. Since 1970, the industry (now EADS Space Transportation) carried out related D & Q programs.

The joint work was at first focused on the 10-cm NSSK engine RIT-10, which was flown onboard "EURECA", lifetime tsted over more than 20,000 hrs, and successfully applied in the "ARTEMIS" rescue mission.

Since the 70ies, rf-engines have been scaled up and tested by the Giessen team or by EADS with 15, 20, 22, 26, and 35 cm of ionizer diam. In addition, spin-off engines for material processing and fusion plasma heating have been developed. Moreover, discharge and beam diagnostic work, thruster modelling, and mission analysis have been performed.

Recently, the Giessen EP-team is engaged in supporting the EADS-tests of the RIT-22 thruster, in investigating of an insertless rf-electron source, in SEP-mission analysis, and especially in scaling-down the standard RIT-10 engine. For microthrusting applications, 4-cm and 2-cm diam RIT-prototypes are under R & D programs.

I. Introduction

A radio-frequency ion thruster of the RIT-type consists basically of a discharge vessel made of an insulating material (quartz or alumina), the induction coil of rf-generator surrounding it, of a multi-aperture two- or three-grid system for beam formation, of the propellant feed system, and of a beam neutralizer. The rf-coil generates an induced electrical eddy field inside the ionizer vessel, which accelerates the discharge electrons. The Maxwellian tail of their distribution ionizes the propellant atoms. The plasma of this inductively coupled, electrodeless, self-sustaining rf-discharge serves as ion reservoir for the beam-forming grid system.

After termination of a thesis on a physical problem of an rf-ion source in 1960[1], the question arose whether the repulsive forces of the extracted ions might be used for space propulsion.

At first view, an rf-source seemed not to be promising in comparison with a dc-discharge engine. Despite the fact than an electrodeless discharge would avoild all problems inherent with discharge electrodes immersed in a plasma, rf-coupling and matching problems as well as the relatively high pressure needed by a self-sustaining discharge looked quite unfavorably. In addition, the rf-discharge had to be ignited by external means. Lateron, another question arose whether harmonics of the rf-generator frequency would disturb spacecraft telemetry.

Thus, the beginning of the RIT-development was characterized by preliminary theoretical and experimental research, by rough calculations, some optimization and diagnostic work and at least by the first test attempts.

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Table 1: Survey on 40-yrs EP-activites at Giessen University

(RIT = rf ion thruster, RIG = rf injector gun, RIM = rf ion source for material processing;
the engine numbers give the ionizer diam in cm)

RIT-systems design, manufacturing, optimisation, and testing at Giessen	
1962 - 1969	RIT-10 L[a),e)]
1970 - 1980	RIT-10 LP (cooperation with MBB/Dasa)[a),b),c)]
1980 - 1998	RIT-10 EM (cooperation with Dasa/Astrium)[b),d)]
1999 - 2000	RIT-GOCE (coooperaton with Dasa/Astrium)[b),d)] RIT-10 for Artemis qualification tests[b),d)]
1968 - 1973	RIT-4 (inhouse activity)[a)]
1968 - 1973	RIT-20 (inhouse activity)[a)]
1974 - 2003	RIT-15 (inhouse activity)[a),c)]
1972 - 1998	RIT-35 (inhouse activity)[a),b),c),d)]
1991 - 1998	ESA-XX (26 cm, ESA-program, Dasa main contractor)[b),d)]
1999 - 2003	RIT-15 for high specific impulse missions (inhouse activity)[c)]
since 2000	RIT-22 (support of Astrium activity)[b)]
since 2004	development of RIT-Microthrusters[c)]
1970 - 2000	work on neutraliser concepts and other thruster components[a),b)]
since 2001	development of an insertless rf-neutralizer[c)]
Spin-off-systems design, manufacturing, optimisation, and testing at Giessen	
1977 - 1988	RIG-10, RIG-15, RIG-20, RIG 10 x 20, RIG 10 x 30 (all [e)]) and RIG-HEX (25 cm x 50 cm)[f)] injector sources (H^+) for fusion plasma heating
1990 - 1996	PRIS-10 NCs cesiated H^- ion injector source
1978 - 1995	RIM-6, RIM-8, RIM-10, RIM-15, RIM-20, RIM-25, RIM-35[g)] and PRIS-10[h)] for material processing
Diagnostics and calculations of RITs, RIGs and RIMs	
since 1965	discharge and extraction calculations, thruster modelling[a),b),c),d),e),f),g)]
1970 - 1998	plasma diagnostics with double probes[a),c),e),f)]
since 1968	beam diagnostics with Faraday cups, mass spectrometry[a),b),c),d),g)]
1977 - 1987	spacecraft charging by high-energy electrons[d)]
1998 - 2000	bolometric ion beam probe
since 2001	energy dispersive ion beam probes
since 1999	design and operation of a 3-axis scanning device
RIT-mission studies	
1968 - 1997	Earth orbit, lunar, planetary and interplanetary missions incl. manned Mars ships
1992 - 1995	cooperation in an European-Russian Joint Study Group, advanced NEP-missions (Fortuna-asteroid, Mercury, Pluto)[c)]
1995 - 1997	EP-Mercury Orbiter and Lander Mission
1999 - 2000	evaluation of enhanced RIT 10 thrusters for the European Earth observation mission GOCE (as subcontractor of Astrium)
since 2005	CONSEP-Contributions to Solar-Electric Propulsion Missions[c)]

support by/in cooperation with

a) German Ministry of Research and Technology
b) MBB/Dasa/Astrium/EADS
c) DARA/DLR-Zentrum
d) ESA/ESTEC
e) German Research Society
f) MPI Garching
g) Companies Pfeiffer, Asslar, and VEECO, N.Y.
h) Company Hauzer, Venlo

II. Past Activities

II.A. RIT-10

The Giessen EP-activities (see Table 1) were concentrated in the beginning on 10-cm class engines.

In 1962, some performance calculations and preliminary test results of a 8.6-cm diameter experimental source were published.[2] The ionizer of this engine was made of teflon. The 4-turns rf-coil was fed by a two-stage electron-tube generator. Trough 17 grid borings, a mercury or xenon ion curent of 7.3 mA could be extracted at 5 kV of beam voltage. In the following, the number of extraction holes was increased to 55, resulting in an Hg^+ current of 39 mA. A filament placed around the extraction area served as beam neutralizer (Fig. 1).[3] At that time, governmental support started.

Then, a new laboratory engine was built and tested. It was equipped with a cylindrical quartz vessel of 10 cm inner diameter and with a 3-grid system having 121 borings.[4] This standard RIT-10 thruster was extensively investigated and optimized in the 2 m^3 vacuum test stand of the institute. The optimizations concerned the discharge vessel length, the rf-generator frequency, the rf-coil geometry, all mechanical dimensions of the grid system, furthermore, the discharge pressure, the rf-power, the extraction voltage, etc. Thruster components like the Hg-vaporizer/isolator system and a hollow cathode neutralizer were investigated, too.[4] In addition, discharge and beam diagnostics were intensified. In October 1966, the primary goal of a 100 mA ion beam current was reached for the first time, and at the end of the decade, a 10-mN laboratory prototype was ready for an industrial advancement.[5,6]

First, the company MBB Munich (now EADS Space Transportation) performed vibration tests of the RIT-10 (Fig. 2), lateron EMI-tests, too. Breadboard thrusters and electronic components were built and tested. By governmental contract, MBB studied also a solar-electric acceleration module "SELAM" of 350 kg of launch mass (Fig. 3), which was planned to be spiralled up by six RIT-10 engines.[6] Unfortunately, this first scheduled space test was not be realized due to budgetary reasons. However, governmental fundings now enabled the institute to build a 30 m^3 vacuum facility "Jumbo", which is still used for thruster testing.

During the second half of the 70ies, the DFVLR Stuttgart joined the national ion thruster testing program and built a lifetime test stand "LEDA", in which four RIT-10 mercury thrusters of MBB (Fig. 4) were tested simultaneously over 8140 h and for more than 4000 cycles, respectively.[7] Following the world-wide trend, the RIT-10 engines were modified for xenon as the propellant in the beginning of the 80ies. The next milestone of the RIT-10 program was the first space test of an European ion engine onboard the European retrievable carrier "EURECA" in 1992 (Fig. 5). The flown thruster assembly "RITA" was built by Dasa (now EADS Space Transportation); the complete flight hardware was checked before in the Giessen facility "Jumbo".[8]

In 1998, a lifetime test of a thrust augmented RIT-10 was started in the large facility at ESTEC Noordwijk. There, the 15-mN engine was operated more than 20,000 hrs without any problems.[9] On July 12, 2001, the 3.1 tons heavy, most advanced communication satellite "Artemis" of ESA has been launched by an Ariane 5. Due to a malfunction of the upper stage, the satellite reached only a useless 31,000-km circular orbit. In this situation it was decided to run the 4 NSSK-ion thrusters onboard (two EITA from Astrium Ltd., Portsmouth, and two RITA from Astrium GmbH, Ottobrunn; Fig. 6) for orbit raising into the GEO. The EP-spiralling up started on April 4, 2002. After the failure of three of the ion engines (operated only for 182 hrs, 521 hrs, and 698 hrs, respectively), the RITA-2 engine finally succeeded in the rescue mission goal, having been operated for 5863 hrs; Artemis reached the GEO on January 31, 2003.[10]

II.B. Scaled-Up Rf-Thrusters

In 1968, two thesis were initiated at the institute concerning both a diminution and an enlargement of the standard RIT-10 engine.[6] A 4 cm thruster RIT-4 was optimized, diagnosed, and tested. At a discharge pressure of $2\cdot10^{-3}$ Torr and a frequency of 9 MHz, 12 mA of Hg^+-ions could be extracted. Due to a lack of applications at that time, the work was terminated in 1973 (see Table 1). In the same period of 1968 till 1973, a laboratory engine RIT-20 with a scheduled thrust of 45 mN was built in the institute's workshop and tested in the Jumbo-facility. The work on this 20 cm device was ended in favour of two other scaled-up rf-ion thrusters, namely a RIT-15 with 50 mN of thrust and a 250-mN engine RIT-35.[8]

Fig. 7 shows the family of the five laboratory RIT-thrusters with 4 cm, 10 cm, 15 cm, 20 cm, and 35 cm of ionizer diameter (photographed around 1975).

Since 1974, several laboratory models of the 15-cm engine were tested at Giessen (first with mercury, then with xenon), reported e.g. 1976 at Key Biscayne, 1984 in Tokyo, 1899 at Garmisch-Partenkirchen, 1991 at

Viareggio, and 1998 in Melbourne.[12] In 2000, an advanced breadboard engineering model RIT-15 was available in two variants, namely for a low and a high specific impulse operation. The two-grid system was made of carbon-composite. A semi-spherical ionizer vessel showed rf-power saving of 23 % in comparison with the standard cylindrical shape. The throttling range of the engine was 2.5 mN to 50 mN.

From 1972 till 1998, two generations of a 35 cm rf-ion engine RIT-35 were investigated in the 30m^3 Giessen test facility and operated with different propellants (Hg, Xe, Kr, Ar, etc.). The first laboratory model was equipped with three 2-mm thick flat grids fixed in the middle by a spacer (Fig. 7).[13] Then, an outward dished grid system, manufactured by Dasa (Fig. 8), showed a sufficiently high mechanical and thermal stability, which allowed extensive and long-term testing programs.[14] The realized thrust level of 250 mN of this RIT-35 prototype was limited only by the available high-voltage generator (2.5 A x 2.5 kV).

At the end of 1992, an ESA/ESTEC-development program of a 26-cm diam primary propulsion thruster "ESA-XX" started. Dasa (now EADS Space Transportation) as the prime contractor built the rf-ionizer; Great Britain and Italy delivered the inward dished grid system and the neutralizer, respectively. Performance tests were carried out by Giessen University in the large Jumbo-facility (Fig. 9).[15] Following a redesign of the thruster, the second-generation engine reached the scheduled thrust level of 200 mN at a beam voltage of 2.2 kV and a total power consumption of 6.7 kW.[12] In 1998, ESA/ESTEC decided not to continue this program towards a qualification procedure. After this decision, EADS Space Transportation started the development and qualification of an own 22-cm rf-thruster RIT-22 (Fig. 10). The company carries out the performance tests in the Jumbo-facility with support by the Giessen EP-team (see below).

II.C. Spin-Off Engines

Based on the experiences gained with the rf-ion thrusters of the RIT-type, two non-propulsive spin-off development lines have been initiated by Giessen University, namely

- the radio-frequency ion sources for material processing of the RIM-family and
- the radio-frequency ion beam generators of the RIG-family designed for fusion plasma heating.

In cooperation with different companies and users, RIM-sources with 4 cm, 6 cm, 10 cm, 20 cm, 25 cm, and 35 cm of ionzer diameter have been developed and tested (Fig. 11).[16] A special design was the 10-cm plasma reactor ion source PRIS-10 equipped with a stainless steel ionizer vessel and an rf-coil immersed in the discharge plasma. The named sources have been operated with didfferent gases like Ar, Kr, Xe, O_2, N_2, CO_2, MgF_2, $CBrF_3$, $CF_2C\ell_2$, SF_6, C_4H_8, etc. The application spectrum reached from target sputtering, texturing, etching of wafers, etc. to the production of thin films by target sputtering, direct deposition or by ion beam assisted vapour deposition. The advantages of the rf-ion source types are their simple construction, the long and reliable operation as well as the possibility to run them with reactive gases, too.

Supported by the German Research Society, the pre-development of fusion injectors started at the institute in 1977 with the investigation of the circular and rectangular rf-ion sources RIG-10, RIG-15, RIG-20, RIG 10 x 20, and RIG 10 x 30.[17] Following a successful check of the RIG-20 in a test bed of the Max Planck Institute of Plasma Physics IPP at Garching, the fusion center and Giessen began a fruitful cooperation in 1984, which was focused on a 25 cm x 50 cm hexagonal rf-source RIG-HEX. The engine could be delivered to Garching in 1988.[18] There, the somewhat modified source has been coupled to a high-voltage grid system (55 kV) producing 100 A of H^+-ions at 120 kW of rf-power (Fig. 12). Now, four "Type-2" rf-injector sources are running at the "ASDEX-Upgrade" fusion machine.

From 1990 till 1996, Giessen Uuniversity was engaged also in a cesiated injector source of the PRIS-type to produce negative hydrogen ions, which are superior to the positive ones for accel voltages exceeding about 250 kV. Caused by a lack of financial support, the program had to be terminated. We mention that the IPP Garching is actually developing an H^--source with rf-excitation of H_2 or D_2 (Fig. 13) for the planned international tokamak experimental reactor "ITER" which will need injector energies of about 1 MeV.

The advantages of rf-ion injector sources are not only their simple construction, their high lifetime and reliability, but also the high atomic species fraction, the low impurity fraction, and especially the possibility to operate the rf-discharge power generator at ground potential.

II.D. Facilities and Diagnostic Equipment

For testing the RIT-, RIM-, and RIG-sources, nine different-sized pumping facilities were at disposal since the middle of the 70ies.

The largest one, called "Jumbo", was initially equipped with two oil diffusion pumps of 50,000 ltr/s, each, with a conical water-cooled stainless-steel beam dump, and with a cylindrical mercury collector cooled by liquid nitrogen. Lateron, an engine hatch (with a 50-cm gate valve) was to added to the 30 m^3 main vacuum chamber.

For testing xenon ion thrusters with mass flow rates up to 50 sccm, the oil diffusion pumps have had to be replaced by 8 helium-cryopumps with an effective pumping speed of 100,000 ltr/s (Xe) and by turbomolecular pumps. From 1999 till 2002, the complete facility has been refurbished (Fig. 14).[9] A special walter-cooled, carbon-covered ion beam target has been installed being able to dissipate beam power levels up to 50 kW at room temperature.

In 2004, another Giessen facility has been refurbished., too. The so-called "Big Mac" test stand was used for spacecraft charging experiments from 1977 till 1987 (see Table 1). Now, the 2.2 m^3 vacuum tank has been equipped with two cryopumps of 12,000 ltr/s, each, with a special thruster mounting frame, and a graphite-coated beam collector (Fig. 15) to test RIT-microthrusters (see below).[19]

Discharge and extraction calculations, thruster modelling and performance evaluation, carried out at Giessen since 1965, were strongly based on extensive discharge and beam diagnostics.

The plasma of most of the above mentioned rf-ion beam sources was investigated carefully by Langmuir double probes. Since 2000, spectroscopic and bolometric measurements complete the thruster diagnostics.

In the first EP-testing facility (2m^3 of volume), a cube-shaped, rotatory beam diagnostic apparatus was installed, consisting of a honeycomb ion collector and a primitive pendulum thrust balance.[5] Later, beam profile measurements were done by a collimated Faraday cup, which could be moved by small motors in three directions.[6] In the 30 m^3 Jumbo-facility, first a swivel arm with 50 Faraday cups and then a propeller-like rotating Faraday rack (1.8 m long, carrying 50 cups) were installed for beam profile mapping.[8,15,16]

In the first half of 2002, this probe rack was replaced by a fast 3D-scanning array of 160 collimated Faraday cups arranged in a line (x-axis), which is movable by stepper motors in y- and z-direction. Thus, three-dimensional beam density profiles are recorded. The system registers the ion flux quickly with a high band width and it is, therefore, able to determine the thrust vector direction and an eventual migration during thruster operation.[9] The thrust in z-direction is measured by a precise pendulum thrust balance.

II.E. Mission Analysis

EP-mission studies based on RIT-engines started at Giessen already at the end of the 60ies: Orbit raising, out-of-the-ecliptic probes, and an asteroid-belt mapping mission were investigated.[20]

During the 80ies, several papers on flight missions to minor celestial bodies, like e.g. the "AGORA" project by using a cluster of RIT-35 einges, were published.[21,22] In 1985, a group of scientists, headed by E. Stuhlinger, proposed a SEP-comet nucleus sample return mission at ESA Headquarters, Paris.[2,3] In the following years, some studies on NEP-Moon ferries and NEP-manned Mars missions were published, and a RIT-100 was scheduled for related applications.[24,25] From 19983 till 1995, a Russian/European Joint Study Group of 34 specialists worked out a study report on "Advanced Interplanetary Missions Using Nuclear-Electric Propulsion" which has been presented at Bonn, Moscow, and Noordwijk.[26] As reference missions, a sample return to the main-belt asteroid "19,Fortuna", a Mercury orbiter and lander, and a Pluto rendezvous have been chosen. The NEP-propulsion module was based on a cluster of 8 ESA-XX ion thrusters and a scaled-up Russian "Topaz" power plant of 25 to 30 kW_e.[27] In Novemer 1996, a group of 9 German/ESTEC specialists proposed at Paris a solar-electric mission to Mercury.[28] Following this proposal, an ESTEC workshop on "Solar Electric Propulsion for Future Planetary Missions" took place at Noordwijk in February 1997. Finally, SEP became a promising candidate for ESA's cornerstrone mission "Bepi Colombo" to the innermost planet of the solar system.

III. Present Activities

III.A. CONSEP-Mission Study

Following the above mentioned, 10 years old NEP-report of the Joint Study Group, the German Aerospace Center DLR, Bonn, concluded a continuation contract "CONSEP" (contributions to solar-electric propulsion) with Giessen on July 1, 2005. The DLR-Institute for Space Simulation at Cologne acts now as subcontractor being responsible for trajectory computation.

The two main goals of the 18-months study are to base the new mission analysis on the present thruster generation (e.g. the RIT-22 instead of the ESA-XX engine) and to investigate modern solar power techniques for missions towards the outer region of the solar system. Solar concentrators, mirrors with photovoltaic and turboelectric converters will be studied. As reference missions, again a "19,Fortuna" asteroid lander (one way and sample return) as well as a SEP-mission to the Jovian icy moon "Europa", which is of outstanding scientific interest, have been chosen. Payload and launch mass of the spaceprobes will be varied as parameters, and the optimum mission profiles will be determined. Finally, NEP and SEP performances should be compared.

III.B. RIT-22 Testing Support and Modelling

As mentioned above, EADS Space Transportation is testing its ion engine RIT-22 partly in the large Giessen vacuum facility "Jumbo". The Giessen EP-group supports the EADS-team, e.g. by operating the vacuum system, by beam analysis, by preparing a cryo-shroud for thermal tests, etc.

One of the EADS measurement campaigns concerned the rf-discharge characteristic giving the extracted ion beam J_i (as the parameter) as function of the required rf-power P_{RFG} and the xenon gas flow rate $\dot{V}$ (Fig. 16 right). Contrary to all former RIT investigations (see e.g. Fig. 16 left),[15] the RIT-22 engine was running so stably (less than one arc per day), reliably and reproducibly, that the characteristic could be computer modelled with high accuracy (mean deviations ≤ 0.3 %). This precise measurement revealed some physically interesting features. E.g., the always used hyperbolic equation (see e.g. Ref. 9 and 25) had to be supplemented by a $b_o \cdot \dot{V}_o$ -term, where $\dot{V}_o$ means the neutral gas losses (being proportional to the discharge pressure):

$$J_i = a(P_{RFG} - w_o J_i + b_o \dot{V}_o)\ (\dot{V} - g_o J_i)$$

The computer fit also showed that w_o and b_o are Boltzmann functions of beam current or plasma density, respectively. Together with the recorded grid voltags and currents and the neutralizer data, an exact modelling of the RIT-22 could be established which entered also the above mentioned CONSEP-study: For the standard beam voltage of 2.1 kV and a throttling range of 50 mN to 175 mN, the thrust-unit power consumption, the total propellant flow rate, the specific impulse, the efficiencies, etc. can be predicted.

In the $J_i(P_{RFG}, \dot{V})$ graph, the throttling lines of a propellant-saving operation (TS-mode) and of a power-saving variant (LS-mode) are drawn and compared (see Fig. 16 right). Actually, the modelling is being extended for a variation of the beam voltage (2.0 - 5.0 kV).

III.C. Rf-Neutralizer

As is well known, the insert and the heater of hollow-cathode electron sources are critical elements for a reliable ion thruster application. A possible alternative of this standard device is to replace these parts by a small rf-discharge which might be excited inductively or capacitively.

By support of the German Aerospace Center DLR, such an insertless and heaterless rf-neutralizer of the capacitive variant is being investigated at Giessen University. In the new prototype (Fig. 17), a dense plasma is generated between 3 x 2 rf-electrodes placed inside the hollow cathode. A magnetic cusp field concentrates the plasma. The aim is to neutralize the discharge ions repeatedly at the hollow-cathode walls and to use in this way each xenon atom for multiple electron delivery.

The generated electrons are drawn along a plasma bridge out of the hollow cathode through a boring of a biased anode ("keeper electrode").

Optimizations of geometry and working parameters are presently worked out, supported by diagnostics using a Langmuir single probe and emission spectroscopy.

III.D. Rf-Microthrusters

During the last years it beame obvious that some scientific missions would benefit from EP-microthrusters producing thrust levels between a few µN up to some 100 µN. The application spectrum comprises the controlled formation flying of spacecraft fleets, a fine-pointing attitude control, an accurate drag compensation, etc.

The question arose whether gridded ion thrusters could be advantageous over cold gas, electrothermal or field emission devices. Within the EP-class, RIT-microthrusters could be favourable with respect to their reliability, lifetime, easy control, and simple construction.

In principle, a RIT-microengine consits only of a ceramic cylinder, sourrounded by the rf-coil, with the gas-feeding at one end of the tube and the two-grid system at the other one. Therefore, the miniaturization of rf-thrusters presents no mechanical difficulties. However, scaling laws show that a reduction of the ionizer size requires higher discharge pressures and frequencies. The ion production costs sould increase (due to the surface-to-volume-ratio) and the efficiencies would consequently decrease.[19]

To find out the optimum geometry and working parameters when scaling-down, a R & D program started at Giessen at the beginning of 2004, supported by the German Aerospace Center DLR.

The tests are done in the above mentioned microthruster facility "Big Mac" (Fig. 15).

Alternatively, a 4-cm and a 2-cm rf-engine are tested (Fig. 18). The RIT-4 device may be equipped with grid systems having 151, 55, 19, or 7 extraction holes. The RIT-2 engine has a standard 7-holes grid-system.[19]

The first tests have been successful: The thrusting ranges of RIT-4 and RIT-2 are between 10 and more than 1000 µN and between 8 and 80 µN, respectively. A stepwise thrust variation is feasible and a 10-hrs test showed a stable operation at acceptable thruster temperatures.

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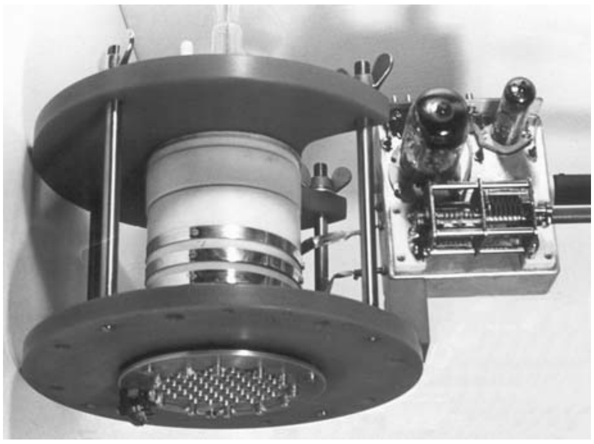


Figure 1. First experimental rf-engine (8.6 cm ionizer diam, 1964).

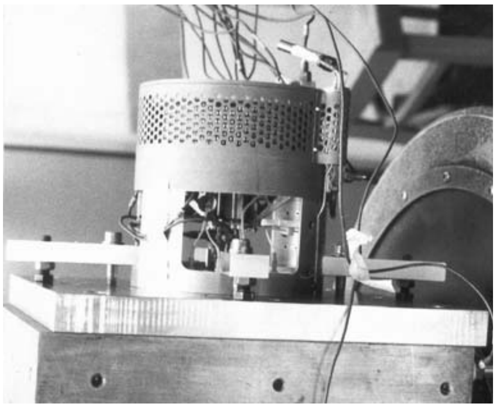


Figure 2. Laboratory prototype RIT-10 LP on a vibration test stand of MBB (1970).

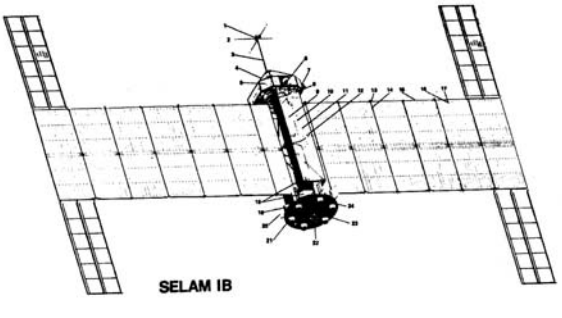


Figure 3. Scheduled solar-electric acceleration module SELAM for space-testing of 6 RIT-10 engines (assessment study by MBB, 1969).

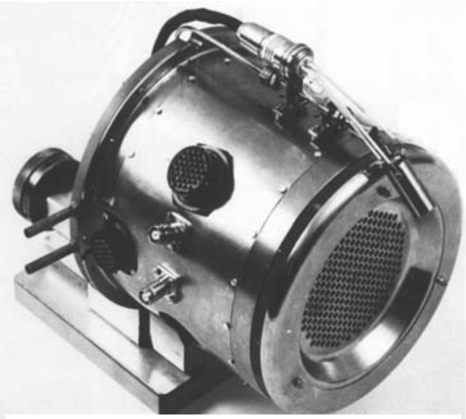


Figure 4. RIT-10 (Hg^+-engine) lifetime-tested at the DFVLR Institute Stuttgart (1977).

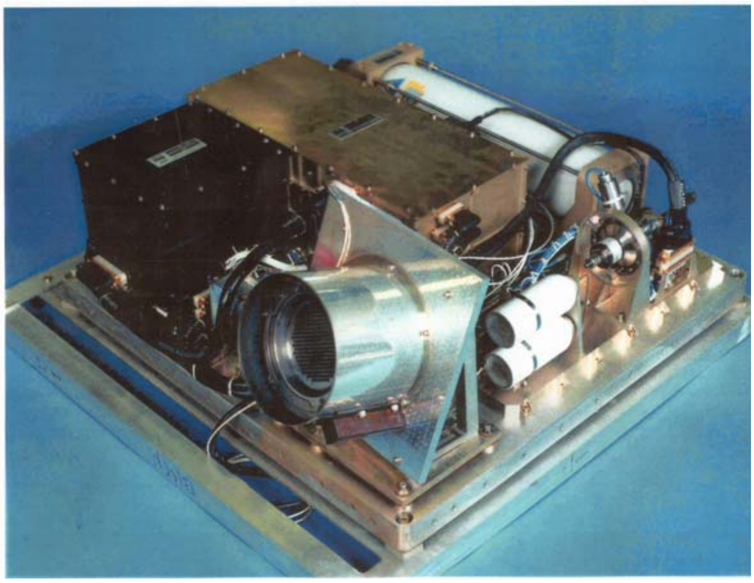


Figure 5. RIT-10 (Xe^+-engine) experimental package space-tested onboard the European retrievable platform EURECA (1992).

Figure 6. Package of two EP-engines (RITA and EITA) onboard ESA's advanced communication satellite ARTEMIS.

Figure 7. Family of 5 laboratory RIT-models of Giessen University with 4 cm, 10 cm, 15 cm, 20 cm, and 35 cm of ionizer diameters (1975).

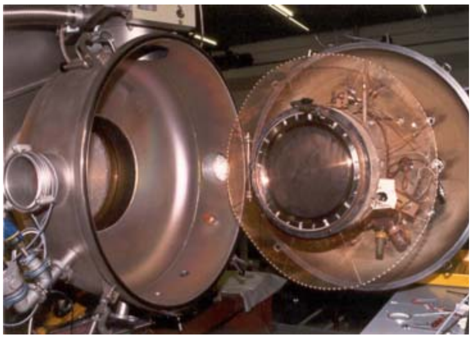


Figure 8. RIT-35 laboratory prototype mounted in the engine hatch of the 30 m^3 vacuum facility of Giessen University.

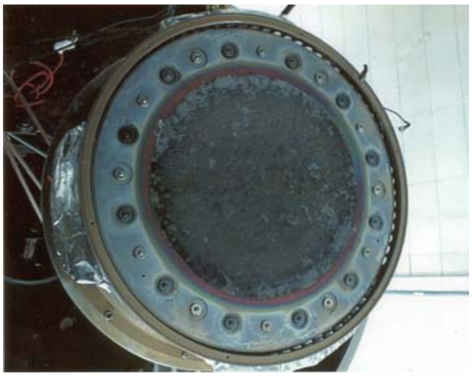


Figure 9. The 26 cm rf-ion engine ESA-XX (main contractor Dasa) after performance tests in the large Giessen test stand (1994).

Figure 10. Two RIT-22 thrusters of EADS Space Transportation tested in the 30 m^3 vacuum facility of Giessen University (2004).

Figure 11. Radio-frequency ion engines for material processing (RIM-family) with 4 cm and 6 cm diam (company Pfeiffer) and with 10 cm and 20 cm diam (Giessen University, 1988).

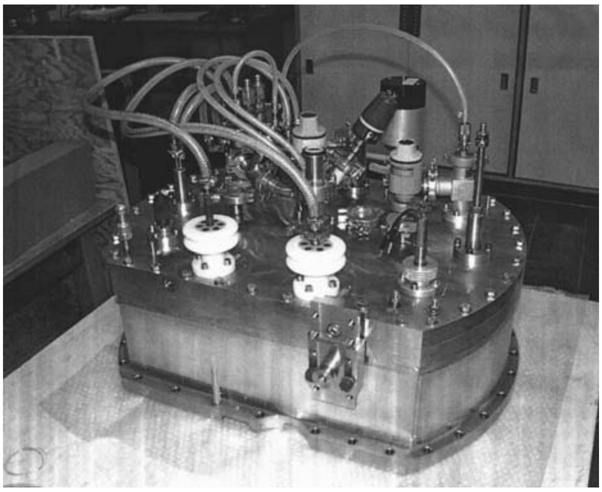


Figure 12. Hexagonal rf-ion injector gun RIG for fusion plasma heating, developed at Giessen (1984 - 1988) modified and applied at the ASDEX-Upgrade machine by the Institute of Plasma Physics of MPI Garching (courtesy MPI, 2005).

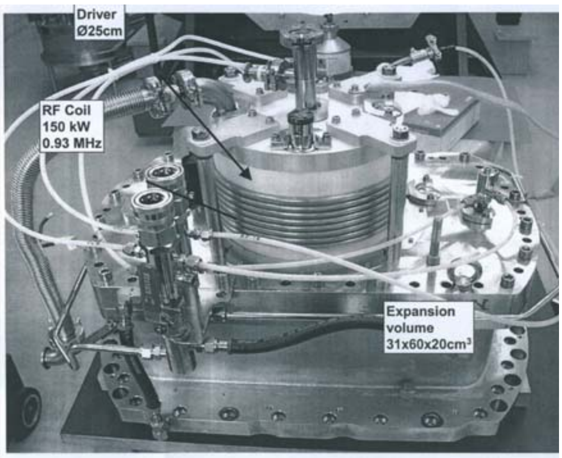


Figure 13. Rf-source to produce H$^-$-ions for theInternational Tokamak Experimental Reactor ITER developed by the Institute of Plasma Physics of MPI Garching (courtesy MPI, 2005).

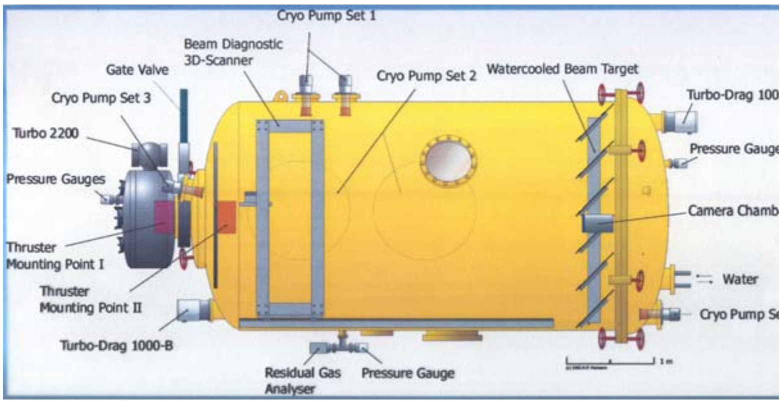
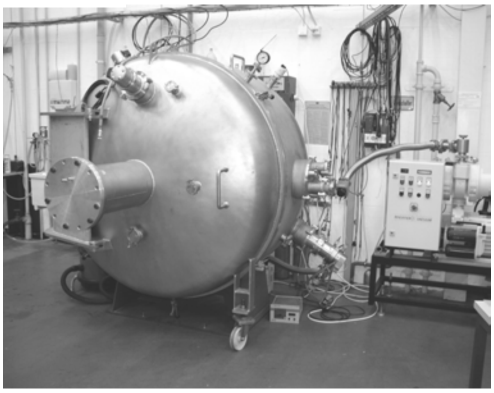


Figure 14. 30 m^3 Giessen vacuum test facility "Jumbo" (100,000 ltr/s pumping speed for xenon).

Figure 15. 2.2 m^3 microthruster facility "Big Mac" of Giessen University (24,000 ltr/s pumping speed for xenon).



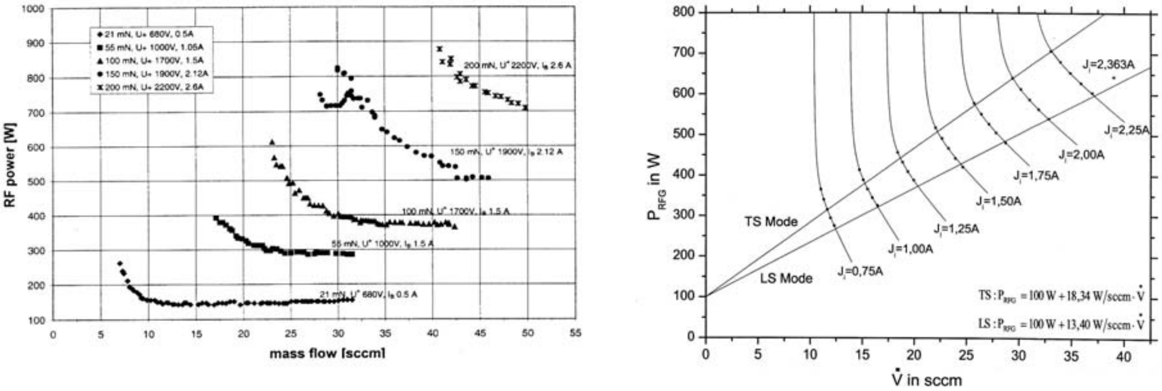


Figure 16. Rf-discharge characteristics of ESA-XX (left) and RIT-22 (right; with throttling lines TS and LS); the beam current J_i depends on the rf-generator power input P_{RFG} and the xenon flow rate $\dot{V}$ through the ionizer; the beam voltage of RIT-22 is 2.1 kV.

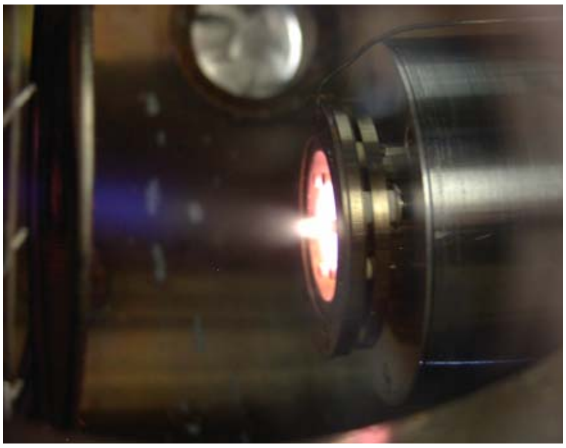


Figure 17. Photograph of the Giessen rf-neutralizer in operation.

Figure 18. Photograph of the disassembled Giessen microthruster RIT-4.