PERFORMANCE OF THE PRIMARY RF-ION THRUSTER ESA-XX

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Abstract

Since end of 1992, Germany, Great Britain and later on also Italy agreed to cooperate for the development of a primary ion motor called ESA-XX. This engine is designed for a nominal thrust of 200 mN using Xenon as the propellant and shall be used as main propulsion for scientific interplanetary missions. The power consumption at the nominal thrust of 200 mN is slightly above 6 kW at a propellant consumption of about 4 mg s.

The ESA-XX motor is based on the German radio-frequency ionization technique developed by the University of Giessen which is used in all RIT thrusters for the generation of the discharge plasma. Ion extraction and thrust generation is performed by a three-grid extraction system with inward dished grids which has been designed and manufactured by Culham Laboratory, UK. An electron source is needed for the neutralization of the ion beam and in the case of radio-frequency thrusters also for starting the main discharge. This task is carried out by a plasma bridge neutralizer manufactured by Proel Company, Italy.

The ESA-XX motor has been assembled at DASA, Munich and integrated in the Jumbo test facility, a large test facility for ion thruster testing, at the University of Giessen. Intensive testing and performance mapping on the ESA-XX engine has been carried out during the years 1994. The thruster performance, as well as thrust and throttling capabilities have been determined. Beside the electrical parameters as ion beam current, accel grid drain current, power consumption, propellant consumption and efficiencies also temperatures have been measured occurring at different locations of the engine which gives an impression of the thermal behaviour and loads.

The available ion beam diagnostic system has been used to examine the current density distribution in the beam at different operation parameters of the thruster and at different distances downstream from the extraction grids. This gives information on the thrust vector and the beam divergence and possible changes of both under changed operation conditions.

The experience gathered with the ESA-XX engine will flow into the development and manufacturing of an ‘advanced laboratory model’ of the ESA-XX which will be carried out under a phase 2 contract in 1995 and 1996. This contract has been kicked off in December 1994 and the work concerning an overall design improved is starting now.

In parallel, additional experiments will be performed with the ‘old’ ESA-XX thruster mainly to study the influence of the neutralization of the ion beam.

1. Introduction

Since three decades, radio-frequency ion thrusters for space applications are a matter of research, development and qualification in Germany. There are two main applications which benefit from the high specific impulse produced by ion thrusters, namely the North-South-Stationkeeping of geosynchronous communication satellites and the use as a primary propulsion system for interplanetary missions, especially such missions characterized by high velocity increments. Using conventional chemical propulsion for such missions, one needs powerful launchers and/or the swing-by technique. This requires complex manoeuvres which benefit from the gravity of the planets to change the flight trajectories in order to reach the final target. However, for flights into the interplanetary space, the absolute thrust requirements are small indeed, but the velocity increment of the propulsion system must be high. Low thrust - high energy, these are the typical characteristics
of electric propulsion systems. By the use of electric propulsion with its roughly ten times higher specific impulse one can save travel time as one can approach the goal directly and the saving of propellant mass allows e.g. higher payloads or a weight reduction. Therefore, the application of electric propulsion promises advantages for high-energetic missions as e.g. multiple rendez-vous and sample return flights to primitive bodies like asteroids and comets, Mars and Mars-moon sample return, outer planet scientific missions, out-of-the-ecliptic probes, or long baseline interferometry [1,2,3,4,5,6].

Two studies of the European Space Agency ESA, a multiple asteroid rendez-vous mission called "AGORA" in 1984 followed by a Comet Nucleus Sample Return mission CNSR, have proposed the implementation of an Electric Propulsion Module, EPM, to drive the scientific probes. These considerations have been the reason to resume the activities on primary propulsion engines placing contracts to DASA MBB and the University of Giessen. Subject of contract was to develop, manufacture, and test an ion thruster capable to produce 200 mN which could be used in the Electric Propulsion Module in clusters of 4 or 6 engines, respectively.

This thrust and power demand has been realized by developing a first prototype of a 35 cm diameter radio-frequency ion source, called RIT 35, at the University of Giessen. This motor has been tested at first using Mercury as the propellant and later on also with the inert gases Xenon and Argon. The first motor has been equipped with a flat three-grid extraction system which has been replaced later by a dished grid version manufactured by DASA Munich. These RIT 35 engines have been completely performance mapped until 1989 [7].

More or less in parallel and in competition for primary propulsion, a second primary engine had been developed in Great Britain by AEA Culham Laboratory, the so called UK 25, which showed similar performance data as the RIT 35 [8]. Since it was considered by ESA that the Europeans could not afford to develop simultaneously two primary engine technologies, efforts have been made to find criteria for a selection of the one or the other engine to be developed further as the European primary motor.

After a period of about two years in which the activities on primary propulsion have been left pending, it has been agreed to continue the work on a European basis involving Germany, the United Kingdom and Italy. It has been decided to develop a primary engine combining the advantages of the technologies having developed in Europe so far. This engine has been named "ESA-XX".

It is based on the German radio-frequency principle for the generation of an electrodeless discharge plasma and uses a British inward-dished three grid system for the extraction of the ion beam. Italy provides plasma bridge neutralizers which are used for beam neutralization and also for the ignition of the main discharge. Since at the time of contract negotiation the thruster size was still unknown it has been agreed to put XX for the size to be determined later on. In the meanwhile, the thruster components have been designed and manufactured, the engine has been assembled and installed in the Giessen Jumbo test facility and the performance mapping has been completed.

2. Design of the ESA-XX Motor

The ESA-XX ion thruster is a propulsion system which has been designed and manufactured in European cooperation. The thruster consists of a German radio-frequency ion source equipped with a British extraction grid system and an Italian plasma bridge neutralizer. The project management has been carried out by DASA MBB who were also responsible for the design and manufacturing of the thruster case and the integration of the engine.

Fig.1 shows a cross section of the ESA-XX laboratory prototype representing the present design. The thruster case consists of three parts, an intermediate cylinder, a back cover and a front ring-shaped cover which protects the grid insulating parts against backspattered material. The rear rim serves also as mounting interface to the flange of the test chamber. All parts are manufactured from aluminium and screwed together.
The total ESA-XX diameter is presently 39 cm with an engine length of 24 cm and including the neutralizer the total length is 26 cm. Actually, the weight of the ESA-XX lab model is about 12.6 kg which shall be reduced below 10 kg after a redesign of the thruster and the very heavy alumina ring for the grid mounting.

As an ion source, the RIT ionizer is used consisting of a quartz discharge chamber of 26 cm in diameter and 10 cm in length. For cost reasons, quartz as material of the discharge chamber has been chosen for the laboratory model but this will be replaced by alumina in a follow-on advanced engine because of its higher mechanical strength. The ionizer is surrounded by 8 windings of the induction coil which is connected to the rf-generator via an impedance matching circuit.

Fig 1. Cross-section of the ESA-XX primary engine

An radio-frequency eddy field is induced in the discharge volume sustaining an electrodeless, annular discharge. In the center of the ceiling of the discharge vessel is the gas inlet distributor with the high voltage insulator, a design similar to other RIT engines. The gas inlet is combined with the extraction anode of the thruster which usually is used to fix the plasma potential. In the ESA-XX engine it is foreseen to use the anode only alternatively, since the screen grid, acting as plasma holder, has been connected to the high voltage supply taking over the extraction anode function during regular operation.

The ion extraction and acceleration is performed by the British inward-dished three grid system. The grids, screen, accel and decel are made of molybdenum. The inward dishing promises a better thermal stability and since the first grid is supposed to be the hottest, short circuits by grid expansion should be avoided. The grid geometry has been chosen following computer simulations carried out by Culham Laboratory using their Sapphire code which has been developed to calculate electric field distributions and ion trajectories. These calculations led to a reduction in the hole size and the grid thickness referred to the conventional RIT grids. Of course, the number of holes increased to 9,097 which is nearly the double of the RIT number resulting in an ion beam diameter of 25 cm.

The spacing between the grids is about 0.75 mm which corresponds to a total extraction voltage of 2.5 kV. The nominal beam voltage for thrust levels above 100 mN is 2.0 kV with an accel grid voltage of -500 V. The decel grid is usually at ground potential but at the ESA-XX it is possible to apply a small negative bias voltage up to -50 V at this grid. The reason for this is to attract charge exchange ions produced in or just behind the grid by this negative bias and thus to prevent them from hitting the accel grid at -500 V. This finally will lead to a reduction of sputtering in the grid system by charge exchange ions because the sputter yield for 50 eV ions is roughly by a factor 100 lower than the yield for 500 eV ions [12]. The three grids are supported by an alumina ring which provides also the electrical insulation and the mounting interface to the discharge vessel and the thruster case.
The plasma bridge neutralizer provides electrons for the neutralization of the ion beam and for starting of the main discharge. It is mounted in a provisional position at the front ring of the engine and slightly canted towards the ion beam. For the first tests, a neutralizer has been used developed for the small RT 10 thruster. This neutralizer is based on the usual hollow cathode technique which is generally used for plasma bridge neutralizers. The small neutralizer has been replaced by a power augmented version which has been used in the tests from October 1994 through February 1995. A still more powerful version is planned to be developed in a next phase contract.

3. Test Set-up and Test Plan

The tests on the ESA-XX thruster are carried out in the Jumbo test facility at Giessen University. This test facility is designed to test different sizes of ion engines. Especially with respect to the ESA-XX tests, the Jumbo facility has been refurbished and improved [9].

In order to meet the reasonable low background pressure of the chamber the effective pumping speed of ~15,000 l/s for Xenon of the two installed diffusion pumps has been augmented by mounting an additional 5,000 l/s turbomolecular pump (see Fig. 2). Together with an additional turbopump of 2.200 l/s on top of the thruster hatch it is now possible to operate ion engines at flow rates in the range up to 50 SCCM which is the equivalent of ~5 mg/s at reasonable background pressures.

The ion engine is mounted in the thruster hatch which is separated from the main chamber by a gate valve. This arrangement allows easy and quick access to the test specimen while the main chamber can be kept under vacuum.

The ion beam diagnostics is placed in the main chamber as sketched in Fig. 2. It allows to measure the mechanical ion beam parameters as the thrust vector and beam divergence. This beam diagnostic device consists of a 1.8 m long boom containing 90 target plates to measure the ion beam current. The boom is supported in the center and turnable like a propeller in order to get a full picture of the beam current density distribution. The boom and its driving motor are mounted on a carriage which can be moved along two rails in the main chamber. This allows a variation of the distance from the engine between 1 m and 2.5 m.

Furthermore, the data acquisition system has been completed now for the tests on the ESA-XX engine. This system is a purpose-designed one for the acquisition of the operational ion source parameters and the evaluation of the recorded data. A special data interface is used for the measurement of voltages, currents, powers, and temperatures.

The ESA-XX engine is supplied by regular laboratory power supply units delivering the positive and negative high voltages for ion extraction and acceleration and the rf-power to sustain the Xenon discharge. The neutralizer is supplied by a separate supply unit consisting of the cathode heater and the keeper discharge supply. Some auxiliary units provide the bias voltage and a constant current source feeds the PT 100 temperature sensors. The Xenon propellant is stored in a high pressure bottle outside of the hatch and through a pressure reducer and two flow controllers the propellant flows into the thruster and the neutralizer.

Measured thruster parameters are the positive and negative high voltages and the corresponding currents, the forward and the reflected rf-power, the neutralizer electron emission and the bias voltage of the decel grid with the corresponding current. The propellant flow rates of the thruster and the neutralizer are measured by two flow controllers which also fix and control the flow rates ac-
According to the chosen set-point. Five additional data acquisition channels measure the temperatures of the screen and decel grid, of the discharge vessel ceiling, of the rf-coil and of the thruster case at the front end opposite to the location of the neutralizer. The thruster is mounted with its rear end to a watercooled flange whose temperature is kept constant by the water at 11°C.

The test procedure for the ESA-XX plans at first some function checks of the propellant feed line, the power supplies, the data acquisition and the beam diagnostic system. In addition, the capacitance between the grids will be measured which is an reliable indicator for proper gaps between the grids. After outgassing and purging of the feed lines with Xenon. the test starts with the activation and the following ignition of the plasma bridge neutralizer which then produces electrons used for main discharge ignition.

A burn-in phase of the thruster follows which is mainly determined by the time necessary for the conditioning of the grid system. The grid conditioning requires to start at low power and low extraction voltage to allow to burn off sharp edges at the grids which are left from the manufacturing process by subsequent arcing. After at least a couple of hours it is possible to establish slowly an ion extraction which improves with time. At thrust levels of 50, 100, 150 and 200 mN the thruster performance has been determined. In parallel, beam diagnostics have been carried out as well as temperature measurements at different points as described above. The neutralizer operation parameters discharge current and propellant flow rate have been changed and the influence on the extracted electron current has been studied.

4 Test Results

4.1 ESA-XX Performance

The ESA-XX development and manufacturing, has been carried out during 1992 and 1993 and the engine has been delivered to University of Giessen at the end of the year 1993. Since some more work was necessary to complete the engine with the thermal sensors and to integrate it into the test facility it took some more weeks until everything was ready to undergo the first test. This has been started in March 1994 with the activation of the neutralizer and its ignition. After this, the main discharge could be started very easily. The attempt to apply the high voltages and extract ions required at first the conditioning of the grid system which again took some time. After a couple of hours, the first ions could be extracted from the ESA-XX engine at low power and low voltage level. Increasing power and voltage levels required additional conditioning periods. Finally, the engine could be performance mapped as planned at the foreseen thrust levels. In parallel to the performance mapping, temperature measurements and beam diagnostic experiments have been carried out. The performance and test results were very promising and are presented in the following part. The basic performance of rf ion thrusters are determined by the rf-power consumption as a function of the propellant consumption for different levels of extracted ion beam current.
These relations are graphed in Fig. 3 for the ESA-XX engine at the specified thrust levels of 50, 100, 150, and 200 mN. The dotted lines at the left hand side of the curves are the borderlines for a 100 % mass efficiency. The ESA-XX demonstrates surprising good efficiencies as ion production cost of about 3.5 W mN could be achieved for the lower thrust levels and even 3.1 W mN for the 200 mN level. It must be mentioned that due to the extraction grid design the nominal beam voltage of 2.0 kV has been applied only for 150 and 200 mN thrust. For the lower thrust levels, 1.75 and 1.5 kV had to be used which changes the specific impulse for these thrust levels.

A further important parameter is the drain current to the accel grid since this current is responsible for the sputtering of the accel grid and this effect is the main lifetime limiting factor. The drain current is composed of two parts, of defocused ions which impinge directly on the grid and of charge exchange ions which are generated in the downstream part of the grid system. The latter are attracted by the negative potential of the accelerator grid. The first part is determined by the grid geometry, the extraction voltage and the plasma density but the rate of charge exchange ions depends on the neutral gas losses and the extracted ion current. This is demonstrated in Fig. 5 where the drain current is depicted as a function of the mass flow rate. It is obvious that the drain current is reduced by reducing the flow rate since less neutrals are available for charge exchange. Of course increases the rate of charge exchange ions with the beam current since the production rate depends on the number of fast ions present in the extraction channel. Fig. 4 shows that the drain current depends linearly on the mass flow rate which means that mainly charge exchange ions contribute to the drain current.

In order to reduce the number of charge exchange ions hitting the accel grid, the influence of a small decel grid bias has been studied applying a voltage up to -50 V to the decel grid. Consequently, the drain current reduces significantly since charge exchange ions are now attracted by the negative decel grid if they are not produced between accel and decel grid. In our case, we observed a reduction by about 40 to 50% of the accel grid current. It could be proved that the missing accel current is more or
less taken over by the decel grid. Fig. 5 shows the dependence of the drain current on the negative bias of the decel grid for different flow rates and different thrust levels. This experiment has demonstrated that biasing of the decel grid could be a tool to reduce the sputtering of the accel grid due to reduced high energy ion impingement as already mentioned earlier.

From the above mentioned basic data one can calculate the thrusters electric and mass efficiency. The electric efficiency is the ratio of the beam power to the total power consumption of the thruster and similar, the mass efficiency is defined as the ion flow divided by the total propellant flow. The total thruster efficiency is the product of electric and mass efficiency and a factor 0.98 which comes from the beam divergence. This total efficiency is graphed in Fig. 6 as a function of the propellant consumption. The ESA-XX engine demonstrates very high efficiencies and consequently also the total efficiency is extremely good in the range of about 80% if the nominal working point of the engine is properly chosen.

The thrusters total power consumption which is the sum of the beam power, the discharge power and the neutralizer power, but not including any power conditioning efficiency, is graphed in Fig. 7 for the studied thrust levels of 50, 100, 150, and 200 mN as a function of the propellant consumption. It could be demonstrated that the measured values e.g. 6.2 kW for the production of 200 mN at a propellant flow of 42 SCCM are well below the scheduled data which were ~ 7 kW power consumption at ~ 60 SCCM propellant consumption.

4.2 Testing of Neutralizer

The performance mapping of the ESA-XX thruster started with a plasma bridge neutralizer developed for the RIT 10 thruster by Proel Company, Florence. This neutralizer is designed for an electron emission of about 250 mA which is of course to low for the application at the ESA-XX. Later in the course of the performance mapping, this neutralizer has been replaced by a bigger one built by Proel Company and based on the hollow cathode of the RIT 10 type but with an enlarged keeper design. This neutralizer can be operated up to 15 W discharge power (instead of 8 W for the small
Sn and shall deliver up to 1 A of electrons. A crosssection of this neutralizer type Ncc A1000 is shown in Fig. 8.

Fig. 8 Cross-section of the plasma bridge neutralizer used for ESA-XX

This neutralizer has been operated by a laboratory power supply unit which allowed to vary the discharge power up to the specified 15 W. The propellant flow to the neutralizer has been controlled by a flow controller and has been set mostly at 1 SCCM, sometimes at 2 SCCM. The influence of the keeper discharge current, the ion beam current and the bias voltage on the electron emission have been studied. The results are given in Fig. 9 and 10.

Fig. 9 Influence of the thruster current on the thruster thrust level

The influence of the ion beam current on the extracted electron current is graphed in Fig. 9 which demonstrates that the electron current increases with increasing ion current but is always well below the equivalent beam current as always observed in ground tests. The electron emission current can be raised by applying higher discharge current or power to the neutralizer discharge. This influence is shown in Fig 10 which includes also the dependence on the application of a small bias voltage.

In general, it turned out that without any bias voltage the emitted electron current was in the same order of magnitude as for the small neutralizer. Applying a negative bias of a few volts gave a higher electron emission up to 0.6 A. The neutralizer mass flow rate had a minor influence on the electron emission and has not been studied systematically. It must be mentioned that also the neutralizer position with respect to the ion beam plays an important role concerning the emission capabilities. However, this subject will be covered by separate studies planned for future experiments.

4.3 Temperature Measurements and Beam Diagnostic

In the following chapter some results of temperature measurements and beam diagnostics will be given briefly.

As mentioned before, temperatures have been measured at 4 different points at the thruster. The quartz discharge vessel reacts very quickly to the power dissipated in the discharge. It reaches roughly 350° C at 200 mN thrust level. The temperatures of the rf-coil and the grids increase much slower. Especially the sensors at both grids suffer from a great thermal inertia according to the complicated mounting. Fig. 11 is a plot of a continuous 6-hour run at 100 mN thrust in which equilibrium temperatures have been reached which are 280° C at the discharge vessel, 230° C at the grids, 220° C at the rf-coil, and 65° C at the thruster case at which the rear mounting interface has been watercooled.

During this 6-hour run all operation data have been recorded and demonstrate the smooth, constant and reliable operation of the ESA-XX. The rf-power consumption, the accel drain current and the thrust level for this period are constant. We recognised that during the 6 hours less than 10 arcs
S,ser occurred which interrupted the influence or the keeper current thrust. ZSA-AA II:520V.

Beam diagnostic measurements have been performed at thrust levels of 50 mN, 100 mN and 150 mN. During the attempt to measure 200 mN beam profiles the diagnostic system has been damaged due to the high thermal load at a beam power of about 5.5 kW.

One example of a 3-dimensional profile of the ESA-XX ion beam is given in Fig.12. This profile has been taken at a thrust level of 150 mN in a distance of 1.75 m downstream the thruster using the beam diagnostic system which has been described detailed in earlier publication [10]. The profile shows the well-known structure of a “sombrero” as achieved also at lower thrust levels. The beam divergence has been calculated to 19° half angle.

Further beam diagnostics have been taken during the 6-hour run in order to compare profiles of the beginning with profiles of the end of the test. Fig.13 gives the variation of the thrust vector and the components of the thrust vector as a function of the operation time. It turned out that the thrust vector moves slightly during the warm-up period of roughly two hours and is practically constant after this time. However, this is insignificant for a main propulsion engine which will be used for continuous operation according to their application.

5. Conclusion

During the test runs of the ESA-XX primary propulsion system it could be demonstrated that the cooperation within this European project led to an excellent ion motor which can and hopefully will become a basic engine for primary tasks. The performance of the engine is better than expected from the planning.

The experiences gathered with this first motor will flow into the design of a next engine which is considered to become an advanced breadboard model / engineering model. This work will be carried out under a phase 2 contract which has been kicked off beginning of 1995 and shall last for about 2 years. The general design will be improved concerning thermal and vibration loads and a bigger neutralizer will be developed under this contract which includes of coarse the parametric testing of the engine. The aim is to reach the maturity to build an EM/EQM of the ESA-XX engine which are necessary steps on the way to a final design and manufacturing of a flight model.
Presently, scientific mission scenarios are under consideration by a European-Russian Joint Study Group which looks for a Nuclear Electric Propulsion stage to drive scientific probes to asteroids, comets, or outer planets including a mission to Pluto. The ESA-XX engine would be the right tool for this ambitious tasks.

6. References


